Examination of Gasification Characteristics of Pressurized Two-Stage Entrained Flow Coal Gasifier* (Comparison of Basic Performance with 2T/D and 200T/D Coal Gasifier)

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The program for the 200T/D coal gasification pilot plant was initiated in 1986 and successfully completed in 1996. In this program, a two-stage pressurized air-blown entrained flow coal gasifier was adopted, jointly developed by Central Research Institute of Electric Power Industry (CRIEPI) and Mitsubishi Heavy Industry, Ltd. using a 2T/D bench scale gasifier. In the 200T/D pilot plant, domestic Taiheiyo coal and Australian Moura, Warkworth coal were used for test operations. The commissioned tests of these three types of coals have been carried out in a 2T/D gasifier, prior to the pilot plant operation. The gasification characteristics of 2T/D and 200T/D gasifiers were evaluated. At the same gasifier air ratio, per pass fixed carbon conversion efficiency of the 2T/D gasifier is about 10% lower than that of the 200T/D gasifier and the heat absorption rate to the gasifier wall of the 2T/D gasifier is about 2% higher than that of the 200T/D gasifier.

Key Words: Gasification, Fossil Fuel Fired Power Generation, Combined Cycle, Coal, Entrained Flow

1. Introduction

For Japan, a country of limited resources, the use of coal, of which the reserves are abundant and supply stability is excellent, as a fuel for power generation is anticipated in the future. However, carbon-dioxide emissions for each calorific unit of coal are more than that of oil and LNG. So, it is necessary to decrease carbon-dioxide emissions by increasing the power generation efficiency. Integrated coal gasification combined cycle power generation (IGCC) can improve the power generation efficiency compared with conventional pulverized coal fired thermal power generation, and the development of IGCC is being advanced

all over the world as a new coal utilization technology.

Our institute and Mitsubishi Heavy Industry set up the bench scale gasifier (2T/D coal gasifier) in 1983 and have developed an original of air blown pressurized two-stage entrained flow gasifier with dry coal feed system. The Japanese government and Japanese electric power industries are actively promoting the development of IGCC, which is considered to be one of the major, next-generation thermal power systems. The 200 T/D entrained flow coal gasification power generation pilot plant project has been conducted by the Engineering Research Association for Integrated Coal Gasification Combined Cycle Power Systems (IGC Association) under the trust of New Energy and Industrial Technology Development Organization (NEDO). The test operation of the pilot plant was started in March 1991 and successfully completed in February 1996⁽¹⁾. In this project, a two-stage pressurized air blown entrained flow coal gasifier was adopted.

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The demonstration of commercial scale plants using an oxygen blown gasifier has already begun in America and European countries, but, technical information concerning the gasification characteristics of each gasifier is rarely made public⁽²⁾.

The authors established the gasification process and the evaluation method of gasification performance for our type of gasifier by the gasification tests using the 2T/D gasifier^{(3),(4)} and have been performing supporting research on the 200T/D gasifier. For the scale up to the demonstration class, it is very important to systematically evaluate the gasification characteristics of 2T/D and 200T/D gasifiers.

In this report, basic gasification characteristics of cold gas efficiency and carbon conversion efficiency, etc. with 2T/D and 200T/D gasifiers are evaluated, and, in addition, the heat absorption rate to the gasifier wall for both gasifiers, in which the scale and the gasifier wall structure are different, is examined.

Nomenclature

- A_c : theoretical air for coal (kg/kg)
 A_{ch} : theoretical air for recycled char (kg/kg)
 C_{cc} : carbon content in coal (wt.%)
 FC_{cc} : fixed carbon content in coal (wt.%)
 C_{ch} : carbon content in recycled char (wt.%)
 FC_{ch} : fixed carbon content in recycled char (wt.%)
 C_{chp} : carbon content in product char (wt.%)
 FC_{chp} : fixed carbon content in product char (wt.%)
 C_{pgc} : carbon content in product gas (wt.%)
 K_s : equilibrium constant of the shift reaction
 $[i]$: volume fraction of gas composition i
 q_{ma} : amount of input air (kg/h)
 q_{mc} : amount of input coal (kg/h)
 q_{mch} : amount of recycled char (kg/h)
 q_{mchp} : amount of product char (kg/h)
 q_{mg} : product gas flow rate (m_N^3/h)
 Q_{hg} : HHV of product gas (MJ/ m_N^3 , wet base)
 Q_{hc} : HHV of coal (MJ/kg)
 Q_{in} : total input heat of coal, recycled char, gasifying agent and recycle gas (MJ/h)
 Q_{out} : total output heat of product gas, product char and discharged slag (MJ/h)
 Q_w : heat absorption rate of gasifier wall (%)
 T : gas temperature (K)
 γ_{pg} : density of product gas (kg/ m_N^3)
 λ : air ratio
 λ_g : gasifier air ratio
 η_{cg} : cold gas efficiency (%)
 η_{cp} : per pass carbon conversion efficiency (%)
 η_{fcp} : per pass fixed carbon conversion efficiency (%)
 η_{cr} : carbon recycle rate (%)

Fig. 1 Structure of 2T/D gasifier

2. Outline of Facility

2.1 2T/D coal gasifier

The structure of the 2T/D gasifier is shown in Fig. 1. The pulverized coal (over 90% passage at 200 mesh) was pressurized in the lock hopper and pneumatically transported to the combustor and the reductor. The char contained in the product gas was collected by cyclone and then recycled to the combustor. The secondary air was fed into the combustor to burn the pulverized coal and the recycled char at high temperature, so that the coal ash was discharged from combustor as molten slag.

The gasifier walls were of refractory material (only the combustor has a water cooled wall). The inner diameter of the combustor was 300 mm, and the gasifier itself was approximately 6 000 mm in height. It had an internal pressure of 2 MPa, and gasified coal at the rate of 100 kg/h (combustor/reductor=40/60). The gas temperature in the combustor ranged from about 1 800 K to 2 000 K, and gas temperature was about 1 300 K at the reductor outlet.

2.2 200T/D coal gasifier

The structure of the 200T/D gasifier is indicated in Fig. 2⁽⁵⁾. The basic concept of the 200T/D gasifier is the same as that of the 2T/D gasifier. However, the 200T/D gasifier differs significantly from the 2T/D gasifier with respect to the following points. Table 1 shows the basic specifications of the 2T/D and 200T/D gasifiers.

- ① All gasifier walls are water-cooled.
- ② Oxygen enriched air is used as a gasifying agent.
- ③ Char is transported by recycle product gas.

Table 1 Specification of 2T/D and 200T/D coal gasifiers

		2 T/D gasifier	200 T/D gasifier
Gasifier type		Pressurized two-stage entrained flow	
Coal feed system		Dry Feed System	
Structure	Combustor	Water-cooled wall	Water-cooled wall
	Reductor	Refractory wall	Water-cooled wall
Capacity		100 kg/h coal	200 T/D coal
Operating pressure		2 MPa	2.7 MPa
Gasifying agent		Air	Air or oxygen enriched air
Transport gas	Coal	Air	Air
	Char	Air	Recycle gas

Fig. 2 Structure of 200T/D gasifier

3. Results and Discussion

3.1 Coal properties

The tested coals are as follows and typical properties of these coals are shown in Table 2.

- ① Domestic Taiheiyo coal with low ash fluid point (1 633 K) and low fuel ratio (0.76)
- ② Moura coal with intermediate level of both ash fluid point (1 713 K) and fuel ratio (1.82)
- ③ Warkworth coal with high ash fluid point of over 1 773 K

3.2 Basic concept of evaluation index for gasification characteristics

2T/D and 200T/D gasifiers have a char recycle system. So, we need to separately evaluate the overall performance (including char recycle system, the area of dotted line in Fig. 3) and gasifier per pass performance (excluding char recycle system, the area of dashed line in Fig. 3). In this paper, air ratio (λ) and cold gas efficiency (η_{cg}) are used for evaluation of overall performance, then, the gasifier air ratio (λ_g), per pass carbon conversion efficiency (λ_{cp}) and per pass fixed carbon conversion efficiency (η_{fcp}) are used for evaluation of gasifier per pass performance. The

Table 2 Typical properties of test coal

	Taiheiyo	Moura	Warkworth
Heating Value(MJ/kg)	27.4	30.0	29.6
Proximate Analysis(%)			
Moisture	5.3	3.7	3.1
Fixed Carbon	35.8	56.2	53.3
Volatile Matter	46.7	30.9	33.2
Ash	12.1	8.7	10.4
Fuel Ratio	0.76	1.82	1.61
Ultimate Analysis(%)			
Carbon	68.2	76.3	74.4
Hydrogen	5.71	4.6	4.84
Nitrogen	0.99	1.54	1.56
Oxygen	12.26	7.31	8.11
Sulfur	0.19	0.46	0.41
Ash Fusion Point(K)			
Initial Deformation	1523	1623	1753
Softening	1588	1683	>1773
Hemispherical	1598	1688	>1773
Fluid	1633	1713	>1773

Fig. 3 Input and output flow around gasifier and definition area for evaluation indexes

definitions of these indexes are as follows.

$$\lambda = q_{ma} / (q_{mc} \cdot A_c) \quad (1)$$

$$\lambda_g = q_{ma} / (q_{mc} \cdot A_c + q_{mch} \cdot A_{ch}) \quad (2)$$

$$\eta_{cg} = [(q_{mg} \cdot Q_{hg}) / (q_{mc} \cdot Q_{hc})] \cdot 100 \quad (3)$$

$$\eta_{cp} = [(q_{mg} \cdot \gamma_{pg} \cdot C_{pgc}) / (q_{mc} \cdot C_{cc} + q_{mch} \cdot C_{ch})] \cdot 100 \quad (4)$$

$$\eta_{fcp} = [1 - (q_{mchp} \cdot FC_{chp}) / (q_{mc} \cdot FC_{cc} + q_{mch} \cdot FC_{ch})] \cdot 100 \quad (5)$$

In case of the 200T/D gasifier, to expand the operational margin of the gasifier and to secure the lower limit of the product gas HHV required for stable combustion in the gas turbine, the air used as the gasifying agent was mixed with the byproduct oxygen obtained from an inert gas production facility before it was injected into the gasifier. The oxygen concentration in the gasifying agent was in the range

from 23 to 25 vol.%(1). In this study, only the data for 25 vol.% is used. Air ratio and gasifier air ratio are calculated from the amount of oxygen contained in oxygen-enriched air.

3.3 Evaluation of overall performance

From past test results of the 2T/D gasifier, the authors confirmed the calorific value of the product gas and the cold gas efficiency at the same air ratio decrease, due to the decrease of carbon recycle rate (η_{cr}) defined by Eq.(6). In addition, the authors proposed the estimation method of the product gas calorific value and the cold gas efficiency from material balance of the gasifier and equilibrium constants (K_s) [Eq.(7)]⁽⁶⁾ of the shift reaction^{(3),(7)}.

$$\eta_{cr} = [(q_{mch} \cdot C_{ch}) / (q_{mchp} \cdot C_{chp})] \cdot 100 \quad (6)$$

$$K_s = ([CO_2] \cdot [H_2]) / ([CO] \cdot [H_2O]) \\ = 0.0265 \cdot \exp(3956/T) \quad (7)$$

The carbon recycle rate of the 2T/D gasifier used in this paper ranges from about 60 - 95%, and there was a tendency for the carbon recycle rate to decrease with a decrease in air ratio. On the other hand, the carbon recycle rate did not depend on the air ratio and was almost 100% for the 200T/D gasifier.

The cold gas efficiency is shown in Fig. 4. The solid lines in these figures are the calculated values for Moura coal obtained from the material balance and the equilibrium constant of the shift reaction at 1350 K (corresponds to the reductor outlet temperature) assuming that the carbon recycle rate is 100%. In the case of the 2T/D gasifier, the experimental data of the cold gas efficiency is slightly lower than the estimated value because of the influence of the carbon recycle rate, especially, the difference increases in the low air ratio where the carbon recycle rate was low. In the case of the 200T/D gasifier, the carbon recycle rate was almost 100% and the difference between the experimental values and the estimated values is very small ($\pm 3\%$, relative value). From the above-mentioned argument, the validity of the estimation method based on the result of the 2T/D gasifier was confirmed for a large-scale 200T/D gasifier, and it was clarified that it was possible to estimate the cold gas efficiency etc. easily and with high accuracy from the material balance and the equilibrium constant of the shift reaction.

3.4 Evaluation of gasifier per pass performance

The authors have evaluated a gasifier per pass performance by mainly using per pass carbon conversion efficiency. The per pass carbon conversion efficiency is a one-through conversion rate of the input carbon contained in coal and recycled char, and indicates a gasification reactivity in the gasifier.

Figure 5 shows the relationship between per pass carbon conversion efficiency and gasifier air ratio.

(a) 2T/D gasifier

(b) 200T/D gasifier

Fig. 4 Comparison of cold gas efficiency between experimental data and estimated value

For both 2T/D and 200T/D gasifiers, the per pass carbon conversion efficiency depends on the gasifier air ratio, and decreases, when the gasifier air ratio is lowered. At the same gasifier air ratio, the per pass carbon conversion efficiency of Taiheiyō coal with a low fuel ratio is the highest. This tendency corresponds to the test result of the 2T/D gasifier, which has been executed up to now^{(8),(9)}.

Because per pass carbon conversion efficiency is a conversion rate which includes the volatile constituent, the conversion rate of only the fixed carbon was examined by using per pass fixed carbon conversion efficiency, which does not contain volatile matter. Figure 6 shows the relationship between per pass fixed carbon conversion efficiency and gasifier air ratio for 2T/D gasifier. Compared with the case of per pass carbon conversion efficiency, it is understood that the difference of per pass fixed carbon conversion efficiency among coal types at the same gasifier air ratio becomes very small. So, the difference of per pass carbon conversion efficiency among coal types originates in the difference of the amount of volatile

(a) 2T/D gasifier

(b) 200T/D gasifier

Fig. 5 Relationship between per pass carbon conversion efficiency and gasifier air ratio

Fig. 6 Relationship between per pass fixed carbon conversion efficiency and gasifier air ratio

matter included in coal.

For high performance of the gasifier, it is important to convert the fixed carbon, not easily gasified, to the gas efficiently. So, the per pass fixed carbon conversion efficiencies of 2T/D and 200T/D gasifiers

Fig. 7 Comparison of per pass fixed carbon conversion efficiency between 2T/D and 200T/D gasifiers

were compared using the results for Moura coal with a lot of data values. Figure 7 shows the comparison result of the per pass fixed carbon conversion efficiency of 2T/D and 200T/D gasifiers. At the same gasifier air ratio, the per pass fixed carbon conversion efficiency of 200T/D gasifier is about 10% higher than that of 2T/D gasifier.

Though the per pass fixed carbon conversion efficiency is influenced by various factors such as the gasifier structure and the operating conditions, the heat absorption rate to the gasifier wall is one of the important factors. That is, the decrease in heat absorption rate to gasifier wall raises the gas temperature, and the per pass fixed carbon conversion efficiency improves because the gasification reaction rate of the fixed carbon increases with the rise of the gas temperature. The result of the examination of the heat absorption rate to gasifier wall of 2T/D and 200T/D gasifiers is described in the next section.

3.5 Examination of heat absorption rate of gasifier wall

The heat absorption rate to gasifier wall is different in the gasifier (especially, combustor part and reductor part). In this paper, the heat absorption rate to the gasifier wall of the entire gasifier (Q_w) defined by Eq. (8) was used to understand the basic tendency⁽¹⁰⁾.

$$Q_w = (1 - Q_{out}/Q_{in}) \cdot 100 \quad (8)$$

Figure 8 shows the heat absorption rate to the gasifier wall of 2T/D and 200T/D gasifiers. From this figure, it is understood that the heat absorption rate of the 200T/D gasifier is about 2–3% lower than that of the 2T/D gasifier at the same gasifier air ratio. The 200T/D gasifier is designed by a similar dimensional standard based on the 2T/D gasifier, and the ratio of the gasifier wall surface area to the volume of the gasifier decreases up to about 20% of the 2T/D gasifier. This becomes a factor which decreases the

Fig. 8 Comparison of heat absorption rate between 2T/D and 200T/D gasifiers

heat absorption rate to the gasifier wall⁽¹¹⁾. But, the entire gasifier wall is water-cooled, and this factor acts to increase the heat absorption rate to the gasifier wall. It seems that the result of these interactions appears as a difference of the heat absorption rate to the gasifier wall of both gasifiers shown in Fig. 8.

The influence of the difference in the heat absorption rate of 2–3% on per pass fixed carbon conversion efficiency was examined. From the result of approximating the straight line for Fig. 8, the heat absorption rate to gasifier wall of 2T/D and 200T/D gasifiers at the gasifier air ratio 0.35 was calculated. Then, assuming that the heat absorption rate of the 2T/D gasifier is the same as that of the 200T/D gasifier, the per pass fixed carbon conversion efficiency of the 2T/D gasifier was estimated. In this estimation, only the gasification reaction by CO_2 shown in Eq. (9) was considered as a gasification reaction of the fixed carbon. As a case where the influence of heat absorption rate becomes maximum, it was assumed that the all of the heat corresponding to the decrease of the heat absorption rate was used for the gasification reaction of the fixed carbon. Moreover, keeping the total input heat to gasifier and gasifier air ratio constant, the amount of input coal, recycled char and input air were not changed, and it was assumed that the amount of the product char decreased by the decrease of absorption heat.

The estimated result and the experimental value are indicated in Table 3. The experimental value of per pass fixed carbon conversion efficiency was calculated by approximating the straight line for Fig. 7. At the gasifier air ratio of 0.35, the experimental value of the heat absorption rate of the 2T/D gasifier is 11.6%, while the heat absorption rate of the 200T/D gasifier is 9.4%, and is lower by 2.2% compared with that of the 2T/D gasifier. When the heat absorption rate of

Table 3 Estimation result of per pass fixed carbon conversion efficiency

	2 T/D gasifier		200 T/D gasifier
	Experiment	Estimation	Experiment
λ_g	0.35	0.35	0.35
Q_w	11.6 %	9.4 %	9.4 %
η_{fcp}	54.2 %	59.0 %	65.0 %

the 2T/D gasifier was changed to 9.4% (equal with 200T/D gasifier), it was estimated that the per pass fixed carbon conversion efficiency improved from 54.2% to 59%. It was clarified that the decrease in the heat absorption rate of 2.2% corresponds to the improvement of the per pass fixed carbon conversion efficiency of 4.8%. However, the per pass fixed carbon conversion efficiency of the 200T/D gasifier is higher than the estimated value. It is thought that factors other than the heat absorption rate to gasifier wall also influence the per pass fixed carbon conversion efficiency of the 200T/D gasifier. As factors other than the heat absorption rate to the gasifier wall, the influences of oxygen concentration in the gasifying agent, pressure and flow situation in the gasifier among others will be examined, and we will try to clarify the effect of each factor on the difference of the per pass fixed carbon conversion efficiency of both gasifiers.

Finally, the scale up from the 200T/D gasifier to the demonstration class gasifier was examined. If the oxygen concentration in the gasifying agent and the structure of the gasifier wall of the demonstration class gasifier are the same as those of the 200T/D gasifier, the heat absorption rate to gasifier wall is decreased in proportion to the decrease of the ratio of the gasifier wall surface area for the volume of the gasifier by the scale up, and it is forecasted that the per pass fixed carbon conversion efficiency improves. In this paper, the per pass fixed carbon conversion efficiency based on the 2T/D gasifier was estimated when the heat absorption rate to gasifier wall changed. The influence of the decrease of the heat absorption rate in the demonstration class gasifier by the scale up on per pass fixed carbon conversion efficiency can be estimated on the basis of a 200T/D gasifier using a similar method to that described in this paper.

4. Conclusion

The authors have established the gasification process and the evaluation method of gasifier performance for the pressurized two-stage entrained flow type gasifier by gasification tests using a 2T/D gasifier. In addition, our institute participated in the pilot plant project, which used a 200T/D gasifier based on our 2T/D gasifier, and we are examining the scale up technology of the gasifier. In this paper, the basic

gasification characteristics of 2T/D and 200T/D gasifiers (the cold gas efficiency, the carbon conversion efficiency etc.) were evaluated. In addition, the examination of the heat absorption rate to the gasifier wall was included and the following conclusions were obtained.

(1) The estimated value of the cold gas efficiency of the 200T/D gasifier corresponded well with the experimental value. It was clarified that it was possible to easily estimate the cold gas efficiency from the material balance and the equilibrium constants of the shift reaction.

(2) The difference among coal types for per pass fixed carbon conversion efficiency except for volatile matter was not remarkable. The difference among coal types for per pass carbon conversion efficiency is caused by the difference of the amount of volatile matter.

(3) The per pass fixed carbon conversion efficiency of the 200T/D gasifier improved by about 10% compared with that of the 2T/D gasifier. The heat absorption rate to the gasifier wall is an important factor which influences per pass fixed carbon conversion efficiency. It was confirmed that the heat absorption rate to gasifier wall of the 200T/D gasifier was 2 - 3% lower than that of the 2T/D gasifier.

(4) The influence of the decrease in heat absorption rate on per pass fixed carbon conversion efficiency was estimated. It was clarified that the decrease in the heat absorption rate of 2.2% corresponds to the improvement of the per pass fixed carbon conversion efficiency of 4.8%.

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