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Experimental Studies of 1 Ton/Day Coal Slurry Feed Type Oxygen Blown, Entrained Flow Gasifier

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Abstract−Experimental Studies of a 1 Ton/Day coal slurry feed type oxygen blown, entrained flow gasifier have been performed with the slurry concentration and gasifier temperature at 65% and above 1,300 °C, respectively. The characteristics of ash fusion temperature with addition of CaO as a flux were investigated to maintain the proper slag tapping condition in the range of reaction temperature. As the flux addition increased, ash fusion temperature showed a eutectic effect with the eutectic at around 20-30% CaO. In order to analyze the gasification characteristics, the effects of O_2/coal feed ratio on the product gas composition, heating value, gasifier temperature and cold gas efficiency were evaluated. From the results, it was shown in the case of Kideco coal that the cold gas efficiency was 44-60% and the heating value was 1,700-2,200 kcal/Nm^3, while Drayton coal showed a cold gas efficiency of 55-62% and a heating value of 1,800-2,200 kcal/Nm^3. In the case of Datong coal, the cold gas efficiency was 38-65%, and the heating value was 2,000-2,300 kcal/Nm^3. Also, the results showed that the optimal operating condition of O_2/coal ratio for the three different coals was 0.9.

Key words: Entrained Flow Gasifier, Coal, Gasification, Slurry

INTRODUCTION

Fossil fuels are reliable and abundantly available sources for primary energy. Although current global proven reserves and production rates for oil and natural gas are expected to last only 40-50 years, the coal reserves are substantially larger than gas and oil reserves; they account for 75% of fossil fuels and are expected to be usable for more than 380 years [Park, 2000]. However, coal combustion results in the emission of gases, such as SO_x, NO_x and CO_2, causing acid rain and global warming.

Recently, stringent environmental regulations and pressures have been mounted on a global scale for the abatement of environmental problems. Therefore, the use of coal for conventional combustion at power plants is confronted by a number of restrictions. There are two ways to achieve efficient and clean coal combustion. The first one is to improve existing technologies, including burning coal briquettes and flue gas clean up, and the second is to use new combustion technologies, including Circulation Fluidized Bed Combustion (CFBC), Pressurized Fluidized Bed Combustion Combined Cycle (PFBC-CC), Integrated Gasification Combined Cycle (IGCC), Partial Gasification Combined Cycle (PGCC), etc. [Yang, 1979; Lee, 1997; Li, 1998].

Integrated Gasification Combined Cycle (IGCC) power generation systems have many advantages over conventional pulverized-coal combustors [Lee, 1999]. These advantages include high energy conversion efficiency and reduced pollutant emissions. Therefore, the IGCC technology is now widely regarded as one of the most practical next generation technologies of coal utilizing power generation technologies that can meet the stringent environmental regulations of the mid-21st century [Yun, 1998]. At the moment, some coal gasifiers for electricity generation such as the Texaco, Shell and Prenflo processes have been constructed and commissioned for commercial operation. However, there still exist a number of problems to be solved for the IGCC systems due to the complicated physical and chemical natures of coal during coal gasification. In particular, a key technology needed for successful performance of IGCC systems is the gasification process, which is mainly influenced by coal type. It should consider various physical and chemical phenomena during gasification, such as coal characteristics, conversion of coal, the heating value of synthesis gases and slagging behavior, etc. Therefore, a number of advanced countries have already concentrated research efforts to develop coal gasification technologies for IGCC.

The slurry feed type entrained-flow coal gasifier has been carefully studied at the Korea Institute of Energy Research (KIER) [Lee, 1996; Park, 1999]. This study was implemented to investigate the complicated nature of coal characteristics and establish the optimal operating condition by using the 1 Ton/Day bench-scale, entrained-flow coal gasifier in KIER.

EXPERIMENTAL

1. Experimental Apparatus

A schematic diagram of the slurry feed type entrained-flow gasifier is shown in Fig. 1. The coal gasifier consists of three sections: the main burner and the auxiliary LPG preheating burner at the top,

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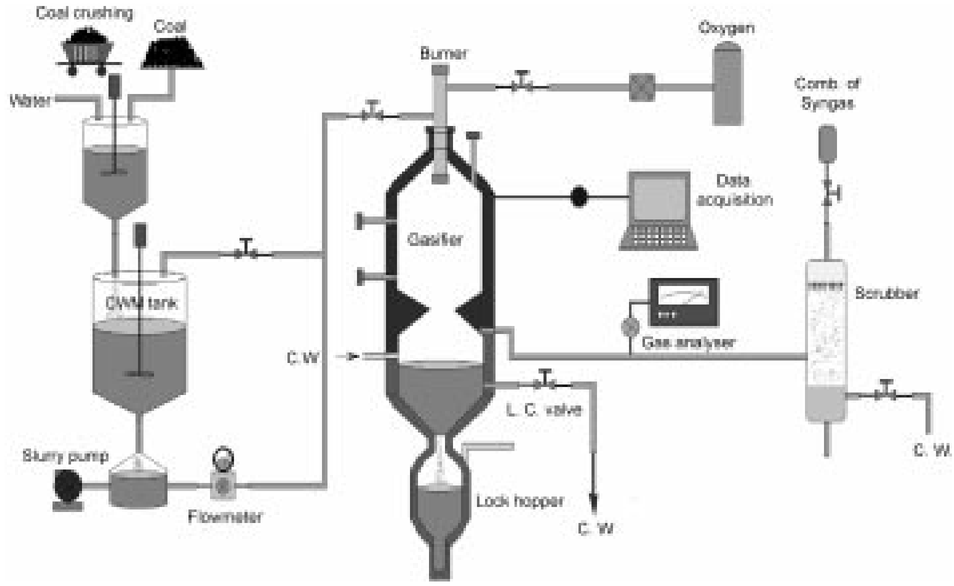

Fig. 1. Schematic flow diagram of 1 T/D slurry feed type entrained-flow coal gasifier.

the reaction zone in the center, and the slag quenching part at the bottom. The reactor consists of three 30 cm sections and one 70 cm section, each with a 20 cm i.d. For the coal feeding system, coal slurry (58-65%, w./w.) is fed into a high pressure reaction vessel lined with high density alumina castable. The coal is coarsely crushed and then wet-ground with slurry water in a two stage vibrating mill to a particle size of less than 200 mesh. The resultant coal slurry is pumped by screw pump and atomized with oxygen through a single burner mounted on the top of the gasifier. In this burner arrangement, the highest temperature was detected near the top of the reactor.

The water in the coal slurry provides the necessary steam for the gasification reactions, where the reaction occurs at 1,200-1,600 °C. The temperature is controlled by variation of the oxygen/carbon ratio, and the steam evaporated from the coal slurry and is maintained at a sufficiently high level to melt the minerals in the coal into a slag. The temperatures of the reaction gas and the reactor wall were monitored by using an R-type thermocouple and 12 K-type thermocouples placed in the reactor wall, respectively. In the gasifier, coal reacts with oxygen and steam evaporated from the coal slurry and partially oxidizes at high temperature, and is converted to multi-component syngas, such as CO, H_2, CO_2 and CH_4. The gasifier is designed to sustain up to 25 kg/cm^2 pressure and is lined with high alumina castable to maintain its high temperature at 1,800 °C. Also a cooling coil is inserted between the castable and the reactor vessel to prevent the reactor shell from over-heating. Coal ash melts and makes slag, which flows down along the gasifier inside wall. The syngas and molten slag are cooled by quenching water at the bottom of the reactor before leaving the gasifier. The quenching water level is controlled by the feedback control system. The ash in the syngas is removed at the syngas scrubber, which further cools the syngas, and is then analyzed and burned at the flare stack. After cooling the syngas, the slag is discharged through the lock hopper. The coal gasification system was designed by considering safety aspects and can withstand high pressure and high temperature. The process control systems of the gasifier integrate with each other and can be easily shut down.

2. Experimental Conditions

The coals used in the experiments were Kideco from Indonesia, Drayton from Australia and Datong from China. The analysis of

Table 1. Analysis of experimental coals

Coal source		Kideco	Drayton	Datong
Proximate analysis (wt%)	Moisture	18.23	5.75	10.62
	V.M	38.99	31.27	27.74
	Ash	2.28	11.73	7.95
	F.C	40.49	51.21	53.69
	H.V (Kcal/kg, HHV)	5,776	6,435	7,020
Ultimate analysis (wt%, daf)	C	59.62	71.93	75.0
	H	6.19	4.94	4.48
	N	0.94	1.57	1.03
	S	0.12	0.61	0.84

Table 2. Analysis of ash composition and fusion temperature

		Kideco	Drayton	Datong
Ash composition (wt%)	SiO_2	32.58	54.02	51.52
	CaO	4.11	4.35	1.59
	Al_2O_3	27.49	34.04	21.02
	Fe_2O_3	21.23	4.26	21.58
	TiO_2	0.68	0.58	0.83
	Na_2O	0.24	0.21	0.43
	K_2O	0.87	0.45	0.91
	MgO	1.85	0.32	0.54
	SO_3	2.30	1.99	0.37
Fusion temperature (°C)	IDT	1,265	1,260	1,223
	ST	1,295	1,580	1,257
	HT	1,325	1,590	1,313
	FT	1,405	1,600	1,328

Table 3. Experimental conditions for the entrained-flow gasifier

Parameters		Gasification conditions
Coal slurry	Coal conc. (wt.%)	65
	Viscosity (cP)	450-1,520
	Temperature (°C)	25
	Feed rate (kg/hr)	58-83
Coal feed rate (kg/hr)		25-50
Oxygen	O_2/coal ratio (wt/wt)	0.6-1.2
	Temperature (°C)	25
Reactor temperature (°C)		1,300-1,550 °C
Reactor pressure (atm)		0-5

coal and ash composition and fusion temperature are shown in Table 1 and Table 2, respectively. Before the injection of coal slurry into the gasifier, the gasifier was preheated to the reaction temperature (1,200-1,300 °C) by using an LPG preheating burner. The experimental conditions in this study are shown in Table 3.

EXPERIMENTAL RESULTS AND DISCUSSION

1. Coal Slurry Viscosity

Coal slurry viscosity is one of the important factors in the slurry feed type gasifier. If the slurry concentration is too low, the reaction temperature inside the gasifier will be decreased, which causes the carbon conversion to decrease. Therefore, it is important to maintain high slurry concentration, but this is difficult due to high viscosity of coal slurry. The coal slurry characteristics should be considered in order to prepare high concentration coal-water slurry while maintaining low viscosity and ideal rheological properties. In the experiments, a surfactant (Formaldehyde condensate of sodium naphthalene sulfonate) was added in the preparation of the coal slurry in order to reduce viscosity as well as to enhance rheological properties of coal slurry [Kim, 1984, 1987]. The slurry viscosities of coals used in the experiments as a function of coal and surfactant concentrations are shown in Fig. 2 and 3. The Fig. 2 indicates that the viscosities of Drayton and Datong coals are too high without

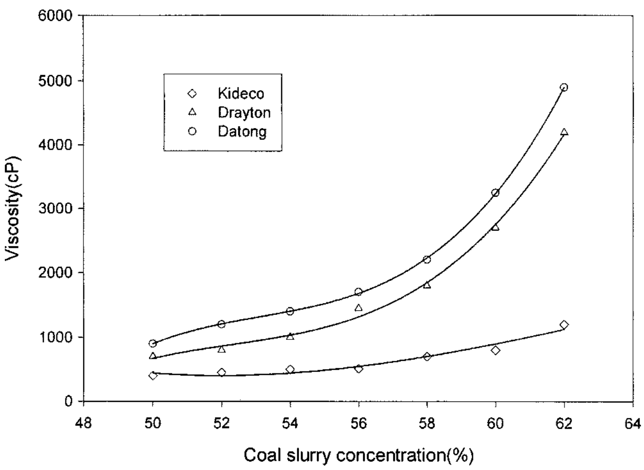

Fig. 2. Variation of coal slurry viscosity with the coal concentration.

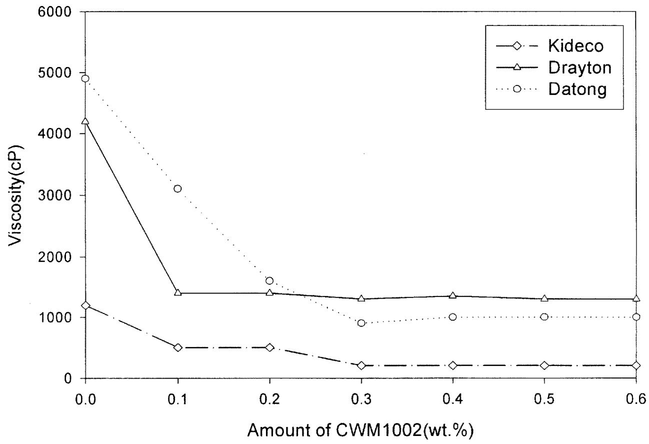

Fig. 3. Variation of coal slurry viscosity with the surfactant concentration.

surfactant. However, as shown in Fig. 3, the viscosities of each coal with 0.3% CWM1002 are maintained below 1,500 cP.

2. Slag Characteristics

The ash fusion temperature of coal is one of the most important considerations for the design of a gasifier as well as the operation because the melting characteristics of ash and slag viscosity have an effect on slag tapping at the temperature of entrained flow coal gasification. The mineral matters in the ash from the coal mainly consist of Al_2O_3, SiO_2, K_2O, MgO, CaO, Fe_2O_3, etc., and the fusion temperatures of the ash were mainly influenced by the aluminum-silicate complex. In order to predict the slag characteristics, many slag indices have been developed by analyzing mineral matters in coal ash such as base/acid ratio, silica ratio, ash fusion temperature, T_{250} [Ikura, 1991]. As the drop in slag melting point is caused by the basic oxide flux, CaO is selected as the best additive in order to reduce ash fusion temperatures. Fig. 4 indicates that the experimental results with Datong coal obtain a minimum ash fusion temperature when flux agent of 20-30% (CaO base) is added to the coal

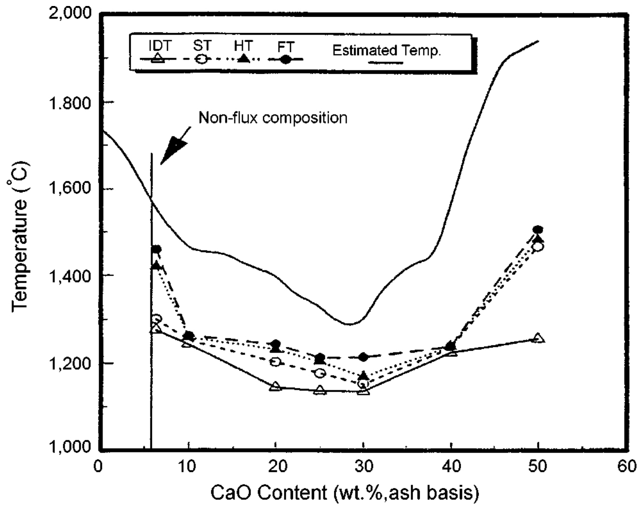

Fig. 4. Measured ash fusion temperature and predicted value in $CaO-SiO_2-Al_2O_3$ phase diagram as CaO addition (Datong Coal).

slurry. Thereafter, ash melting temperatures are gradually increased at CaO concentration over 30%.

3. Gasification Results

When coal slurry is injected into a high-temperature gasifier, a series of physical and chemical processes will occur in the coal gasifier. The particles are quickly heated and the moisture is evaporated, then the volatile matter is devolatilized and the char is burned or gasified. At the same time, the gaseous products from the coal particles will be fired or react with other species according to the surrounding environment and their intrinsic kinetics mechanism. Physical and chemical processes in coal gasification are similar to processes in coal combustion [Smoot, 1993]. One of the main processes is still coal combustion, i.e., exothermic heterogeneous reaction of carbon from coal with oxygen to produce carbon monoxide and carbon dioxide as shown in reaction 1 and 2.

$$C+O_2 \rightarrow CO_2 \quad (1)$$

$$C+1/2O_2 \rightarrow CO \quad (2)$$

The char-steam gasification reaction (Reaction 3) and char-CO_2 reaction (Reaction 4) are endothermic and must rely on the heat from the exothermic combustion reactions.

$$C+H_2O \rightarrow CO+H_2 \quad (3)$$

$$C+CO_2 \rightarrow 2CO \quad (4)$$

The heterogeneous reaction of carbon with hydrogen (Reaction 5) is exothermic and produces methane.

$$C+2H_2 \rightarrow CH_4 \quad (5)$$

In addition to the heterogeneous reactions above, three exothermic homogeneous reactions, combustion of carbon monoxide and hydrogen and water-gas shift reaction (Reactions 6, 7 and 8, respectively), are also important.

$$CO+1/2O_2 \rightarrow CO_2 \quad (6)$$

$$H_2+1/2O_2 \rightarrow H_2O \quad (7)$$

$$CO+H_2O \rightarrow CO_2+H_2 \quad (8)$$

In this study, the O_2/coal ratio was changed in order to analyze the effects of O_2/coal ratio on syngas output, heating value, temperature change of the gasifier and cold gas efficiency. During gasification, the slurry concentration and gasifier temperature were maintained at 65% and about 1,500 °C, respectively.

In general, when the coal slurry feeding rate is constant, if the O_2/coal ratio increases and then the reaction temperature is high, reaction 4 becomes active and consumes CO_2 from reaction 1. This causes CO_2 concentration in the product gas to decrease. However, if O_2/coal ratio is very high and O_2 supply is in excess, CO_2 concentration increases very rapidly and the reaction is mostly under combustion. In the case of the Texaco gasification pilot plant using Illinois coal, CO_2 concentration decreases as O_2/coal ratio increases, becomes minimum at O_2/coal ratio of 0.8 and then increases very rapidly [Wen, 1979]. The effect of O_2/coal ratio on the gas composition of Kideco, Drayton and Datong coals is presented in Fig. 5. As shown in this figure, the CO_2 concentration of Kideco and Drayton coals increases when the O_2/coal ratio is above 0.8, while CO_2 concentration of Datong coal is at a minimum at a O_2/coal ratio of 0.9. However, syngas (CO and H_2) concentration for each coals decreases gradually as the O_2/coal ratio increases and is about 45-75%. Fig. 6. shows the change of heating value of the three different coals with respect to O_2/Coal ratio. As shown in this figure, the heating value decreases when the O_2/coal ratio increases. The obtained heating value of Datong coal is the highest and varies from 1,500-2,300 kcal/Nm^3. This figure indicates also that the optimal operating condition of O_2/coal ratio is about 0.9. The effect of O_2/coal ratio on the gasifier temperature is presented in Fig. 7, which shows that the gasifier temperature increases as the O_2/coal ratio increases. This can be explained by the carbon conversion. The increase of O_2/coal ratio favors the exothermic reactions 1 and 2, which causes the reactivity of coals to be high and leads to a higher carbon conversion and gasifier temperature. The ash fusion temperatures of Kideco,

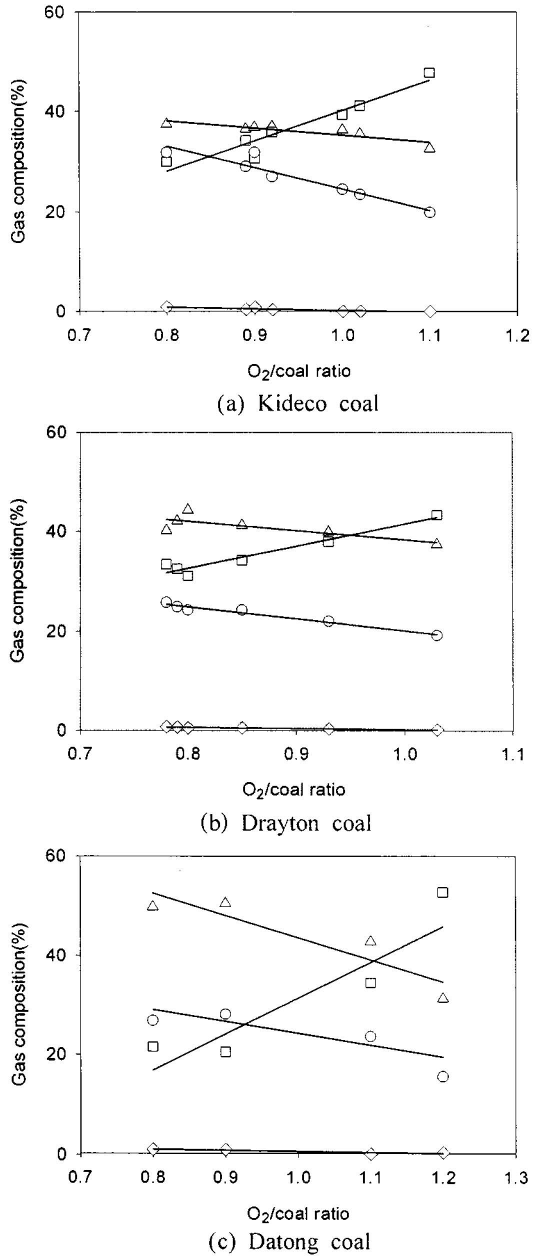

Fig. 5. Gas composition changes with respect to the O_2/coal ratio (△: CO, □: CO_2, ○: H_2 and ◇: CH_4).

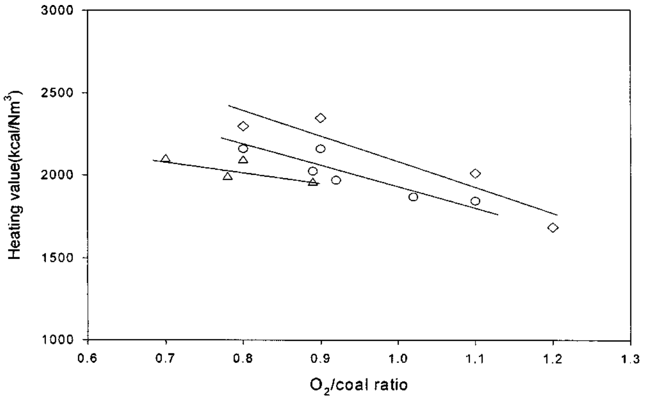

Fig. 6. Heating value changes with respect to the O_2/coal ratio (○: Kideco, △: Drayton and ◇: Datong).

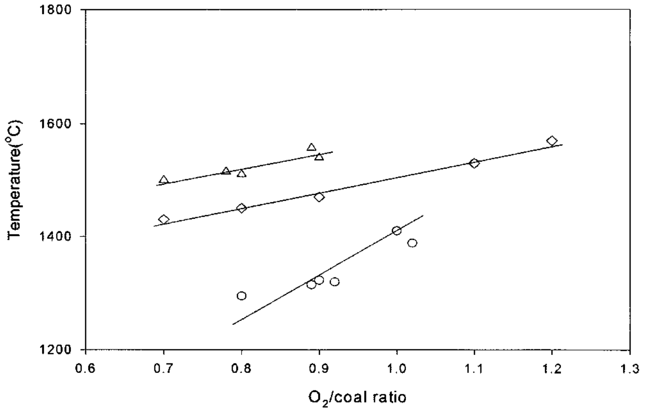

Fig. 7. Gasifier temperature changes with respect to the O_2/coal ratio (○: Kideco, △: Drayton and ◇: Datong).

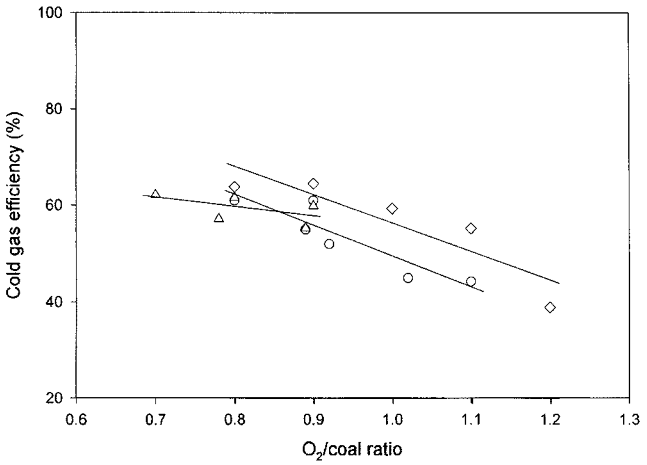

Fig. 8. Cold gas efficiency changes with respect to the O_2/coal ratio (○: Kideco, △: Drayton and ◇: Datong).

Drayton and Datong coals in Table 2 are 1,400 °C, 1,600 °C and 1,300 °C, respectively. Therefore, the gasifier temperature should be maintained above 1,400 °C, 1,600 °C and 1,300 °C, respectively. This means that O_2/coal ratio should be maintained between 0.9 and 1.0. The change of cold gas efficiency with respect to O_2/coal ratio is shown in Fig. 8. The cold gas efficiency decreases when the O_2/coal ratio increases and is about 45-65%. And the maximum cold gas efficiencies are obtained near an O_2/coal ratio of 0.9.

CONCLUSION

From the experimental gasification of Kideco and Drayton coals in the entrained flow coal gasifier, the following conclusions were obtained:

1. 0.3 wt% of CWM1002 added in the preparation of coal slurry reduced viscosity and enhanced rheological properties of the coal slurry.
2. The variation of ash fusion temperature with addition of CaO as a flux was investigated to maintain the slag tapping condition at the reaction temperature in the entrained flow coal gasifier. As flux addition increased, ash fusion temperature decreased to a minimum value of around 20-30% CaO and then increased.
3. For gasification, the slurry concentrations and gasifier temperature were maintained at 65% and above 1,300 °C, respectively. In order to analyze the gasification characteristics, the effects of O_2/coal ratio on product gas composition, heating value, gasifier temperature and cold gas efficiency were plotted. As a result of the experiments, it was shown in the case of Kideco coal that the cold gas efficiency was 44-60%, 50-65% for syngas and that the heating value was 1,700-2,200 kcal/Nm^3, while the results for Drayton coal showed that the cold gas efficiency of 55-62%, 60-72% for syngas, and a heating value of 1,800-2,200 kcal/Nm^3. In the case of Datong coal, the cold gas efficiency was 38-65%, 50-79% for syngas and the heating value was 2,000-2,300 kcal/Nm^3.
4. The optimal operating condition of O_2/coal ratio was obtained at near 0.9. Datong coal had a higher reactivity compared with the two other coals.

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