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# Enhancement of Combustion Efficiency with Mixing Ratio during Fluidized Bed Combustion of Anthracite and Bituminous Blended Coal

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**Abstract**−In order to investigate the effect of mixing ratio of bituminous coal to blended coal on the enhancement of combustion efficiency, combustion experiments of blended coal with anthracite and bituminous are done in a laboratory scale fluidized bed combustor (10.8 cm ID and 170 cm height). The gross heating values of anthracite and bituminous coal used in this study are 2,810 cal/g and 6,572 cal/g, respectively. Experimental parameters are fuel feed rate, superficial gas velocity and mixing ratio of bituminous coal to blended coal. The combustion efficiency increases with the mixing ratio of bituminous coal due to the lower unburned carbon losses and higher burning velocity of bituminous coal. The rate of combustion in the combustor was increased with mixing ratio resulted from a higher burning velocity of bituminous coal. The measured combustion efficiency experimentally is about 3.5-12.4% higher than that of the calculated value based on the individual combustion of anthracite and bituminous coal under the same operating conditions. The optimum mixing ratio (MR) of bituminous coal determined is around 0.75 in this study.

Key words: Blended Coal, Anthracite, Bituminous, Mixing Ratio, Fluidized Bed Combustion

## INTRODUCTION

The estimated amount of coal, which occupies almost all of the reserves in Korea, attains 1.5 billion tons. However, about 40 percent of the coal is low-grade anthracite coal which has around 4,000 kcal/kg [Choi et al., 1983]. Therefore, the utilization methods of the coal must be developed on the maintenance of the coal industry and the security of reserves.

The studies for a utilization method of low-grade anthracite coal were performed in various ways inside and outside of the country [Jung et al., 1988; Song et al., 2001]. Previous reports, however, indicate that the direct combustion of coal in a fluidized bed combustor is the most effective.

A number of significant advantages of fluidized bed combustion include intensive mixing, effective gas-solid contact, high heat and mass transfer rate, high thermal stability and uniform temperature distribution in the bed. The sulfur dioxide released from the burning fuel can be chemically captured by the limestone addition in the combustion process without additional treatment facilities for flue gas. The formation of thermal-$NO_x$ is also held to a minimum as a result of the low operating temperatures (about 800-900 °C). Among the various types of combustion equipment, therefore, the fluidized bed combustor has become a popular choice for the low-grade coal combustion and the incineration of wastes [Sarofim, 1977; Radovanovic, 1986; Taylor, 1978; Anthony et al., 1985].

As previously mentioned, the low-grade anthracite coal of high ash content and low calorific value can be combusted effectively in a fluidized bed combustor. However, combustion efficiency of anthracite coal is sluggish due to low burning velocity and calorific value. Also, the feed rate of fuel must be increased to maintain the higher intensity of combustion (about 250-500 kw/m$^3$); then the combustion efficiency decreases because the elutriation rate of unburned fine particles increases [Lee et al., 1990, 1992].

Several investigations on overall combustion characteristics of blended coal of bituminous and anthracite coal in a fluidized bed combustor have been already performed [Park et al., 1993; Oh et al., 1995; Choi et al., 1996]. In fluidized bed combustion, size distribution of coal, fluidizing velocity, operating temperature and pressure drop in the bed were generally considered as major parameters which were significantly influencing the combustion characteristics. It is expected that the pressure drop in the combustor, the elutriation characteristics of fine particles, and combustion characteristics will be changed with mixing ratio of bituminous in blended coal combustion in comparison with individual combustion of anthracite or bituminous coal.

To establish the effective utilization of low-grade domestic anthracite coal, therefore, a combustion experiment with the addition of bituminous coal is carried out in a lab-scale fluidized bed combustor. The combustion characteristics are investigated with operating parameters such as the fuel feed rate, superficial gas velocity, bed temperature and mixing ratio of bituminous coal to blended coal.

## EXPERIMENTAL

### 1. Apparatus

The lab-scale combustion system was composed of a fluidized bed combustor (FBC), fuel feeder, air compressor, LPG bomb, and temperature and pressure measuring systems. The schematic diagram of the experimental setup is shown in Fig. 1.

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‡This paper is dedicated to Professor Dong Sup Doh on the occasion of his retirement from Korea University.

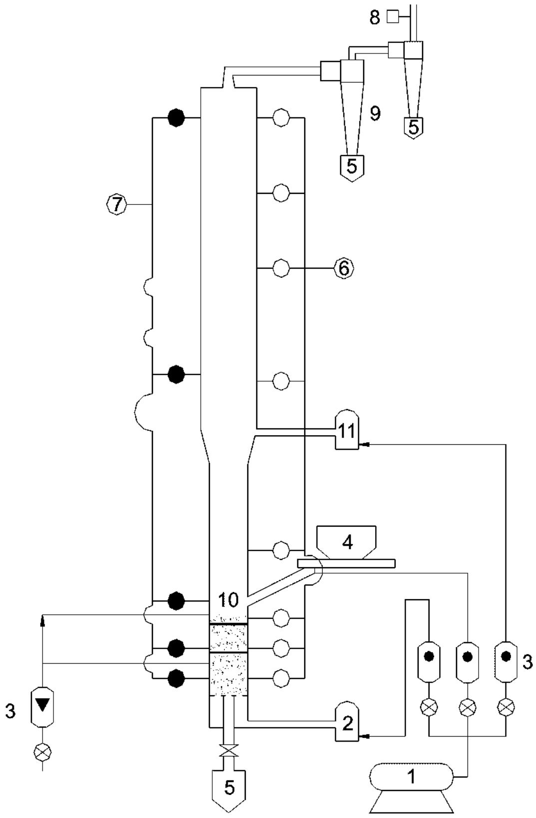


**Fig. 1. Schematic flow diagram of FBC.**

| | |
|---|---|
| 1. Air compressor | 6. Thermocouple and recorder |
| 2. LPG bomb | 7. Differential pressure gauge |
| 3. Rotameter | 8. Gas analyzer |
| 4. Coal hopper & screw feeder | 9. Cyclone |
| | 10. Cooling line |
| 5. Ash hopper | 11. Second air injector |

The combustor was fabricated from stainless steel. The specifications of FBC are 170 cm of total height, and 10.8 cm ID but enlarged to 15.8 cm ID at the axial location of 70 cm above the distributor. A stainless steel plate with 36 perforations of 0.2 cm diameter (1.2% open area ratio) in a triangular arrangement was used for the air distributor.

To measure the temperature and pressure, eight thermocouples and five pressure taps were installed at different height of the combustor. A gas sampling port was installed at the exit line of the 2nd cyclone which was arranged to collect the fine particles. In order to control the bed temperature, a cooling tube was inserted horizontally into the bed. The whole combustor was insulated with ceramic wool of 20 cm thickness.

**2. Procedure**

For the combustion experiments, the initial bed was charged with 1,100 g of anthracite coal-derived ash which had −10~+20 mesh size range. To start the combustor, combustion air from the compressor was divided into a primary and secondary flow. The bed was fluidized by the primary air preheated, and the secondary air was injected into the freeboard section of 70 cm above the distributor. The LP gas was mixed with the primary air in the plenum chamber, and induced into the bed through the air distributor. The LPG was supplied until the bed reached the ignition temperature (Anthracite 700 °C, and Bituminous 600 °C). Then the air flow and the coal feed rates were gradually increased until the bed temperature reached a predetermined value.

The coal was fed quantitatively into the bed by a screw feeder through the location of 50 cm above the air distributor. The ash in the bed was drained through the underdrain tube installed at the center of the air distributor. The height of the fluidized bed was maintained at 20 cm by the controlling of the ash drain rate based on the pressure drop in the bed.

When the combustion reached a steady state, bed and freeboard temperatures and gas compositions were measured. The ashes drained from the bed and collected by the cyclone collectors were weighed once an hour and analyzed to obtain the combustible losses. From these data, the combustion efficiency (η) in Eq. (1) was calculated on the basis of the heating values.

$$\eta = 100 \times \left[ 1 - \frac{F_b \times H_b + F_c \times H_c + F_g \times H_g}{F_0 \times H_0} \right] \quad (1)$$

where $F_0$, $F_b$, $F_c$ and $F_g$ were coal feed rate, ash drain rate from the bed, carryover rate, and flow rate of combustible gas in the flue gas, respectively. $H_i$ is the heating value of each outflow stream.

**3. Operating Conditions and Testing Material**

The ranges of the experimental conditions are listed in Table 1 in terms of various operating parameters. The coal used in this study is the bituminous and low-grade anthracite coal, whose compositions and heating values are shown in Table 2. In addition, particle size distributions of the coal crushed as 2 mm under size and passed the screw feeder are listed in Table 2.

## RESULTS AND DISCUSSION

**1. Individual Combustion Characteristics of Coal**

To investigate the shrinkage properties of coal particles during the combustion process, the coal was completely burnt in an electric furnace. The size distribution of ash and coal samples was plotted in Fig. 2. As shown in Fig. 2, anthracite coal-derived ash was not shrunken, but the fraction of fine particles in the bituminous coal-derived ash was increased highly. This can be attributed to the fact that the combustible content in the bituminous coal is much higher than that in the anthracite coal as shown in Table 2. In addition, the fragmentation of the bituminous coal particles by thermal shock occurred severely in high temperature combustion condition. From

**Table 1. Experimental parameters and conditions**

| Parameters | Conditions |
|---|---|
| Bed temperature, $T_b$ (°C) | 750-900 |
| Fuel feed rate, $F_0$ (g/min) | 14.41-52.38 |
| Fluidized bed height (m) | 0.2 |
| Air/fuel ratio, $\lambda_T$ (-) | 1.2 |
| Superficial gas velocity, $U_0$ (m/s) | 0.7-1.3 |
| Bituminous mixing ratio, MR (-) | 0.0-1.0 |
| Primary air factor, PAF (-) | 0.8 |

MR(−): The ratio of bituminous coal to blended coal based on a heating value basis

PAF(−): The ratio of primary air flow rate to total air flow rate at standard state (273 K, 1 atm)

**Table 2. Compositions and particle size distributions of anthracite (A) and bituminous (B) coal used in the experiment**

| Items | A-coal | B-coal | Items | A-coal | B-coal |
|---|---|---|---|---|---|
| Proximate analysis (wt%) | | | Particle size distribution (wt%) | | |
| Moisture | 2.12 | 6.55 | Size range (mm) | | |
| Volatile matter | 6.06 | 18.58 | 2.00-0.84 | 33.67 | 37.68 |
| Fixed carbon | 41.25 | 62.15 | 0.84-0.60 | 12.95 | 13.18 |
| Ash | 50.57 | 12.72 | 0.60-0.30 | 18.40 | 16.89 |
| Ultimate analysis (dry basis, wt%) | | | 0.30-0.21 | 7.92 | 7.52 |
| C | 38.58 | 73.89 | 0.21-0.15 | 7.57 | 6.39 |
| H | 0.35 | 3.91 | 0.15-0.10 | 3.58 | 3.09 |
| N | 2.24 | 3.94 | 0.10-0.07 | 5.43 | 3.92 |
| S | 0.35 | 0.36 | <0.07 | 10.48 | 11.33 |
| O | 6.81 | 4.29 | $\bar{d}_p$ (mm) | 0.194 | 0.199 |
| Ash | 51.67 | 13.61 | Calorific value(cal/g) | 2810 | 6572 |

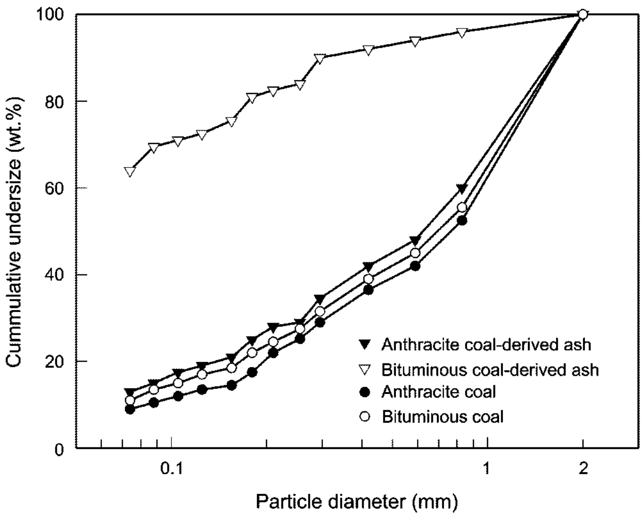


**Fig. 2. Particle size distribution of coal and ash samples after combustion in electric furnace.**

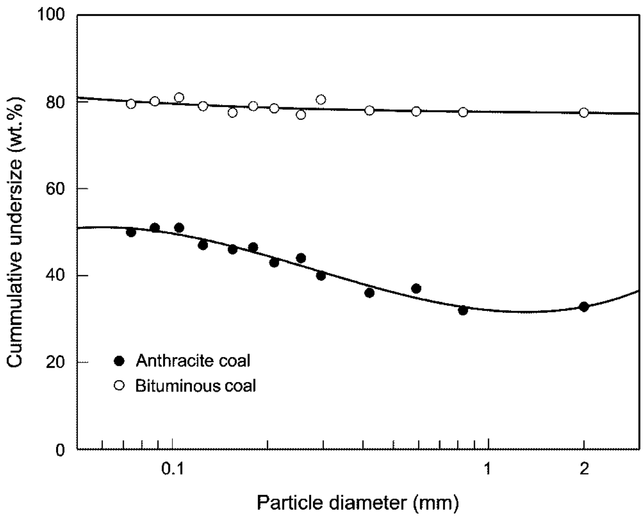


**Fig. 3. Combustible contents with regard to particle diameter of anthracite and bituminous coal.**

these results, therefore, it was found that the fragmentation phenomena of the bituminous coal particles will be intensified, and thus most of the ash particles will be entrained with the gas stream without ash being retained in the bed. However, the anthracite coal-derived ash can be used as a bulk bed material without an addition of any bed materials.

Fig. 3 shows the combustible contents with particle size of anthracite and bituminous coal. As shown in Fig. 3, the combustible contents of anthracite coal were decreased with increasing the particle size of coal. Therefore, the combustion efficiency can be decreased with increase in the entrainment of unburned fine particles. However, the combustible contents of bituminous coal were uniform with various particle sizes.

Generally, the bed materials that have been used in the fluidized bed combustor are sand, aluminum oxide or limestone. In our previous reports [Lee et al., 1988, 1990, 1991, 1992; Jang et al., 1992]; however, it was found that the anthracite coal-derived ash can be used as a bed material due to the lower attrition rate in the bed. To determine the addition rate of bed material, therefore, the bed pressure drop was measured with operating time after a steady state condition in the fluidized bed combustor of anthracite and bituminous coal, respectively, and was plotted in Fig. 4. In the case of anthracite coal combustion, as shown in Fig. 4, the pressure drop increased from 11 cm $H_2O$ to 18 cm $H_2O$ after steady state condition. This means there was an increase in the accumulation of the anthracite coal-derived ash in the bed continuously.

On the contrary, the pressure drop was constant for 24 hrs as 11 cm $H_2O$ during the bituminous coal combustion. This means the bituminous coal ash does not remain in the bed. The bituminous coal has lower ash content (<10%), and higher fine particles produced by the particle shrinkage, fragmentation, and attrition during the fluidized bed combustion process.

To maintain a constant pressure drop in the bed during the fluidized bed combustion of anthracite coal, the bed material had to be drained at a fixed rate through the underdrain tube which was positioned at the center of the air distributor.

### 2. Combustion Characteristics of Blended Coal

The elutriation and underdrain rates of ashes with mixing ratio of bituminous coal to blended coal were measured to determine the particle discharge rate in the fluidized bed combustion of blended

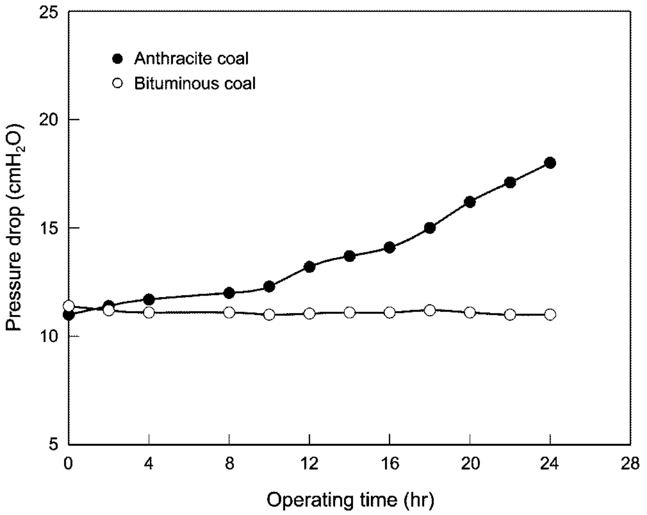


**Fig. 4. Variation of pressure drop through the bed with regard to operating time.**

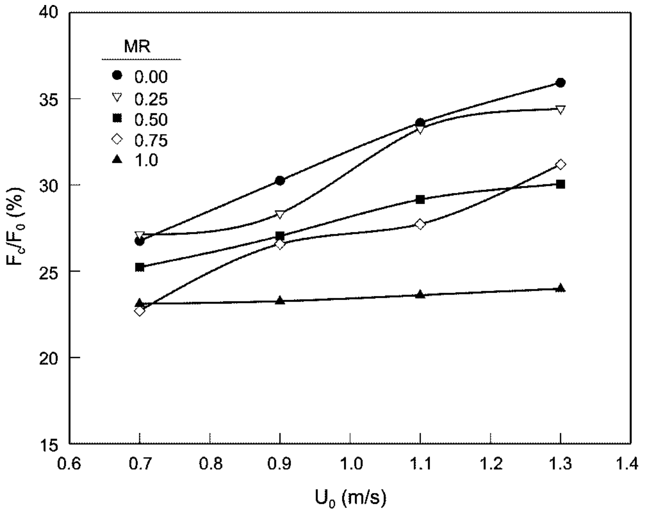


**Fig. 5. Variation of carryover rate with regard to superficial gas velocity ($U_0$) and mixing ratio (MR): ($T_b$=850 °C, PAF=0.8, $\lambda_T$=1.2).**

coal with anthracite and bituminous coal. Figs. 5 and 6 show the elutriation rate ($F_c/F_0$) and the underdrain rate ($F_b/F_0$) of ashes, where $F_0$ is the feed rate of coal into the combustor, $F_b$ and $F_c$ are the discharge rate (g/min) of underdrain ash particle and collected particle by cyclones, respectively.

As shown in Fig. 5, the elutriation rates ($F_c/F_0$) of fine particles from the bed increased with an increase in the superficial gas velocity. In fluidized bed combustion, the critical particle diameter of elutriated particles from the bed was determined by the relative velocity, which is the difference between the superficial gas velocity and particle terminal velocity. When the superficial gas velocity increases, therefore, the elutriation rate of particles increases due to increase of the critical diameter of the elutriated particles.

At the same superficial gas velocity, the elutriation rate of particles also increased with decrease of the mixing ratio (MR) of bituminous coal to blended coal. This can be attributed to the fact that the

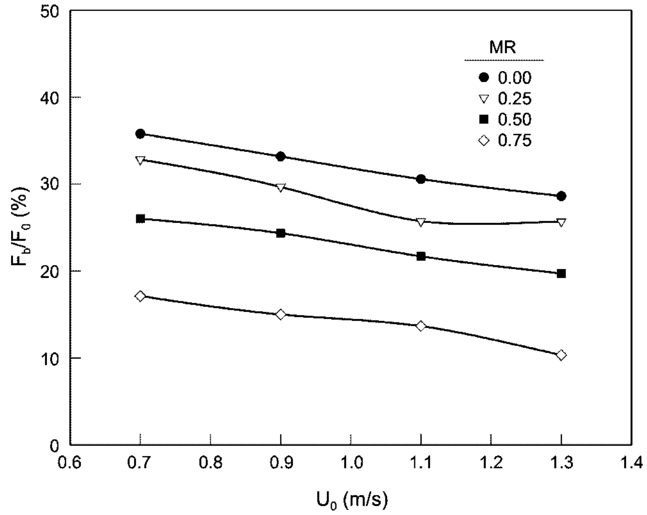


**Fig. 6. Variation of underdrain rate with regard to superficial gas velocity ($U_0$) and mixing ratio (MR): ($T_b$=850 °C, PAF=0.8, $\lambda_T$=1.2).**

total feeding rate of coal increased, and the fraction of anthracite coal in the fed coal increased with the decrease of the mixing ratio. In a practical combustion process, even if the tendency of the fineness of the bituminous coal was higher than that of anthracite coal, the losses of unburned carbon were limited, and also the weight fraction of bituminous coal-derived ash in the elutriated particles was lowered due to the lower ash content and higher burning velocity of bituminous coal. As previously mentioned, therefore, the elutriation rate decreased with increase of the mixing ratio.

Fig. 6 shows the underdrain rate of the ash in the bed with gas velocity and mixing ratio. As shown in Fig. 6, the underdrain rate ($F_b/F_0$) decreased with increase of the superficial gas velocity. The fraction of particles remaining in the bed decreased due to an increase in the gas velocity. Also, the underdrain rate decreased with increasing the mixing ratio of bituminous coal due to the decreases of the remaining particle fraction of anthracite coal in the bed.

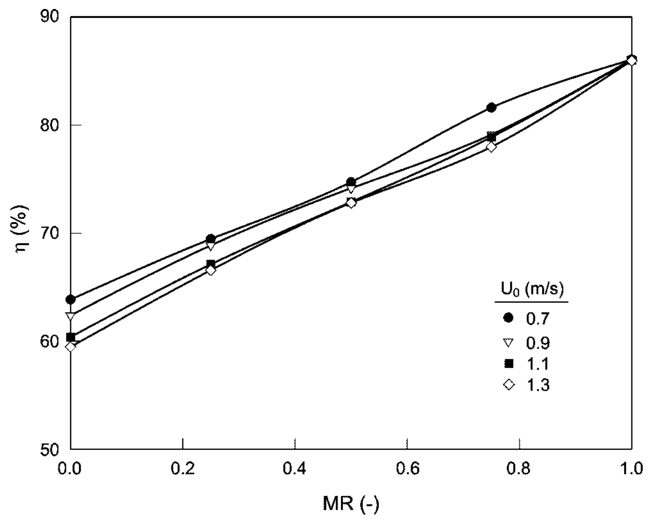


**Fig. 7. Variation of combustion efficiency with regard to mixing ratio in FBC: ($T_b$=850 °C, PAF=0.8, $\lambda_T$=1.2).**

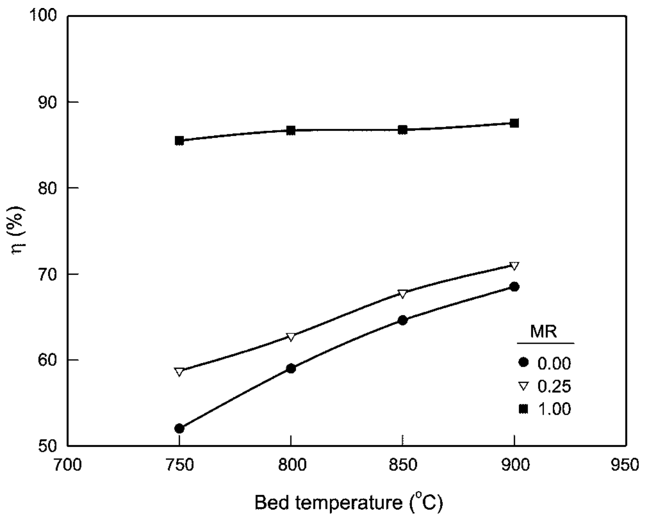


**Fig. 8. Comparison of combustion efficiency with regard to bed temperature: ($U_0$=1.1 m/s, PAF=0.8, $\lambda_T$=1.2).**

Major parameters which affect the combustion efficiency are the bed temperature and the unburned carbon losses by the elutriated and the underdrained particles, and the emitted CO in the flue gas. In these parameters, the unburned carbon loss by the elutriated particles is the most effective parameter.

Fig. 7 shows the combustion efficiency with the various gas velocities and the mixing ratio, under the condition of constant total air-fuel ratio. The combustion efficiency tends to increase as the increase in the mixing ratio, and decreasing the gas velocity. This implies that the rate of combustion in the combustor was increased by increasing the mixing ratio of the bituminous coal which has high burning velocity. As previously mentioned in Fig. 6, the underdrain rate and combustible content in the ash were decreased with an increase in the gas velocity, but the critical diameter of elutriated particles increased due to the higher drag force on the particles. Therefore, the combustion efficiency decreased somewhat with the superficial gas velocity.

Fig. 8 shows the effect of bed temperature on the combustion efficiency. As shown in Fig. 8, the combustion efficiency of the anthracite coal (MR=0.0) increases remarkably with increase of the bed temperature. In contrast, the combustion efficiency of the bituminous coal (MR=1.0) increases about 2% only (from 86% to 88%) when the bed temperature is increased from 750 °C to 900 °C. From these results, it is found that the burning velocity of the anthracite coal is increased markedly with increase of the bed temperature, and then the combustion efficiency increases with bed temperature.

The combustible content in the outflow ash streams varies according to the various operating conditions. As the mixing ratio increases, however, the burning velocity of the fed coal increases, and thus the combustion efficiency increases by the excellent heating value of the bituminous coal.

In order to find the optimum mixing ratio, the characteristics of ash streams and combustion efficiencies with operating conditions were investigated in a fluidized bed combustion of blended coal (see Table 3). As shown in Table 3, the elutriation rate of fine particles tends to decrease with an increase in the mixing ratio. This can be attributed to the fact that the rate of combustion of the bituminous coal mixed, which has higher combustible content, is in-

**Table 3. Comparison of mass flow rate of outflow ash and combustion efficiency between experiment and calculation ($T_b$=850 °C, $\lambda_T$=1.2, PAF=0.8)**

| $U_0$ (m/s) | MR (-) | $F_0$ (g/min) | Ash drain and elutriation rate (%) | | | | Efficiency (%) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | $F_b/F_0$ | $F_c/F_0$ | $(F_b/F_0)_{cal}$* | $(F_c/F_0)_{cal}$* | $\eta_{exp}$ | $\eta_{cal}$* | $\eta_{exp}-\eta_{cal}$ |
| 0.70 | 1.00 | 14.41 | 0.00 | 23.11 | 0.00 | 23.11 | 86.07 | 86.07 | 0.00 |
| | 0.75 | 18.15 | 17.13 | 22.70 | 27.11 | 25.88 | 81.61 | 69.25 | 12.36 |
| | 0.50 | 21.71 | 26.02 | 25.24 | 29.50 | 26.12 | 74.72 | 67.76 | 6.96 |
| | 0.25 | 24.03 | 32.83 | 27.13 | 32.35 | 26.41 | 69.46 | 66.00 | 3.46 |
| | 0.00 | 28.21 | 35.80 | 26.76 | 35.80 | 26.76 | 63.85 | 63.85 | 0.00 |
| 0.90 | 1.00 | 18.53 | 0.00 | 23.26 | 0.00 | 23.26 | 86.06 | 86.06 | 0.00 |
| | 0.75 | 23.33 | 15.00 | 26.58 | 25.12 | 28.56 | 79.11 | 68.13 | 10.98 |
| | 0.50 | 27.92 | 24.36 | 27.04 | 27.33 | 29.02 | 74.15 | 66.55 | 7.60 |
| | 0.25 | 32.18 | 29.68 | 28.34 | 29.97 | 29.58 | 68.86 | 64.67 | 4.19 |
| | 0.00 | 36.26 | 33.18 | 30.25 | 33.18 | 30.25 | 62.38 | 62.38 | 0.00 |
| 1.10 | 1.00 | 22.66 | 0.00 | 23.61 | 0.00 | 23.61 | 86.00 | 86.00 | 0.00 |
| | 0.75 | 28.52 | 13.67 | 27.73 | 23.15 | 31.17 | 78.88 | 66.60 | 12.28 |
| | 0.50 | 34.12 | 21.69 | 29.16 | 25.19 | 31.84 | 72.88 | 64.89 | 7.99 |
| | 0.25 | 39.37 | 25.73 | 33.27 | 27.62 | 32.63 | 67.11 | 62.85 | 4.26 |
| | 0.00 | 44.32 | 30.57 | 33.60 | 30.57 | 33.60 | 60.38 | 60.38 | 0.00 |
| 1.30 | 1.00 | 26.77 | 0.00 | 23.98 | 0.00 | 23.98 | 85.95 | 85.95 | 0.00 |
| | 0.75 | 33.70 | 10.33 | 31.19 | 21.67 | 33.03 | 77.98 | 65.90 | 12.08 |
| | 0.50 | 40.32 | 19.72 | 30.06 | 23.58 | 33.83 | 72.80 | 64.13 | 8.67 |
| | 0.25 | 46.49 | 25.70 | 34.42 | 25.85 | 34.78 | 66.56 | 62.03 | 4.53 |
| | 0.00 | 52.38 | 28.62 | 35.93 | 28.62 | 35.93 | 59.47 | 59.47 | 0.00 |

*Calculated values based on the ash drain and elutriation rate of the individual combustion of anthracite and bituminous coal.

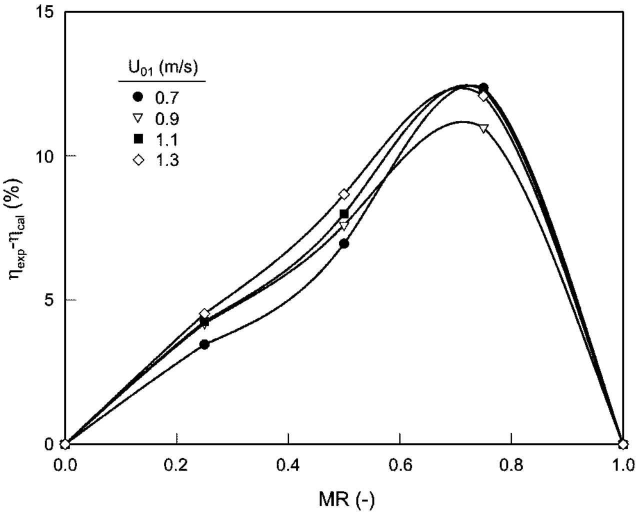


**Fig. 9. Comparison of experimental and calculating combustion efficiency in FBC: ($T_b$=850 °C, PAF=0.8, $\lambda_T$=1.2).**

creased in the freeboard section, and thus the temperature of the freeboard section is increased. Consequently, the combustion of unburned fine particles of anthracite coal, which is passed through the freeboard section with combustion gases, has actively taken place.

From these results, it can be found that the enhancing effect of combustion efficiency appears by an increase of the combustion rate of the anthracite coal which has low burning velocity. The enhancing effect of combustion efficiency with the mixing ratio in a fluidized bed combustor is shown in Fig. 9. The measured combustion efficiency is 3.46-12.36% higher than the calculated value based on the ash drain and elutriation rate of the individual combustion of anthracite (MR=0.0) and bituminous coal (MR=1.0). The bituminous coal added promotes the burning velocity of the anthracite coal, and thus the combustion rate of the anthracite coal increases. Therefore, the combustion efficiency increases with the mixing ratio of the bituminous coal. The optimum mixing ratio of bituminous coal is estimated to be 0.75 in this study. It is equivalent to 0.24 in weight ratio of the bituminous coal to the blended coal.

However, an increase in the gas velocity results in a decrease in the combustion efficiency due to increase of the elutriation rate of unburned fine particles. Therefore, more advanced combustion technology must be developed to overcome the elutriation problem and to generate more heat energy.

## CONCLUSIONS

To investigate the combustion characteristics of blended coal, combustion tests were performed with the various parameters in a laboratory scale fluidized bed combustor. The results obtained in this study are as follows:

The bituminous coal-derived ash did not remain in the fluidized bed due to the lower ash content and shrinkage characteristics of the coal in the combustion process. However, anthracite coal-derived ash accumulated in the bed, and resulting in an increased pressure drop through the bed. As a result, the bottom ash has to discharge by using the underdrain pipe during combustion.

The elutriation rate of fine particles tends to increase with the superficial gas velocity, and the underdrain rate of bottom ash decreases during fluidized bed combustion of the blended coal with bituminous and anthracite coal. But the elutriation rate of fine particles tends to decrease with increasing the mixing ratio of the bituminous coal to the blended coal because of the higher burning velocity of fine particles in the freeboard.

The enhancing effect of combustion efficiency with the mixing ratio of bituminous coal is about 3.5-12.4% higher than the calculated combustion efficiencies of anthracite and bituminous coal in fluidized bed combustion under the same operating conditions. The optimum mixing ratio of the bituminous coal determined is to be 0.75 in this study.

## NOMENCLATURE

$F_0$ : fuel feed rate [g/min]
$F_b$ : weight of particles drained from the bed [g/min]
$F_c$ : weight of particles collected in cyclones (carryover) [g/min]
$F_g$ : flow rate of combustible gas in exit gas stream [g/min]
$H_0$ : heating value of feed fuel [kJ/kg]
$H_b$ : heating value of particle drained from the bed [kJ/kg]
$H_c$ : heating value of carryover particles [kJ/kg]
$H_g$ : heating value of combustible gas in the exit gas stream [kJ/kg]
MR : the ratio of bituminous coal to blended coal based on a heating value basis [-]
PAF : the ratio of primary air flow rate to total air flow rate at standard state (273 K, 1 atm) [-]
$T_b$ : bed temperature at 20 cm above the air distributor [°C]
$\eta$ : the combustion efficiency [%]
$\lambda_T$ : total air-fuel ratio to theoretical air flow ratio [-]

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