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Thermochemical and combustion behaviors of coals of different ranks and their blends for pulverized-coal combustion

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HIGHLIGHTS

► A laboratory-scale slit burner was used to study combustion characteristics via thermal analytical results.
► The coal rank could affect the characteristic temperature such as the ignition and burnout temperature.
► The fuel ratio influenced the flame lengths and mean flame temperatures of the blended coals.
► The blending showed non-additive behaviors between the parent coals and their blends.
► There were some correlations between the characteristic parameters from TGA and the combustion region.

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ABSTRACT

In this research, a laboratory-scale slit burner, which accurately represents the conditions of a practical flame with a high heating rate and jet velocity, was used to study the combustion characteristics using thermal analysis. Results of thermogravimetric and differential thermal analyses (TGA and DTA) showed that low-rank coals influenced the ignition temperatures of blends whereas high-rank coals influenced their burnout temperatures. The first-order differential method was used to determine the kinetic parameters for coals of different ranks and their blends. Additionally, in pulverized-coal flames with CH^* chemiluminescence band intensity, three reaction regions (Zone I: preheating, Zone II: volatile matter reaction, and Zone III: char reaction) were identified. The length of the reaction region and the mean flame temperature were found to be close to those for coal with a higher fuel ratio in Zone I. In Zone II, the fuel ratio influenced the length of the reaction region, but the mean flame temperature was closer to that for the low-rank coal and the maximum combustion reactivity shifted to a lower position. Moreover, the correlation between TGA and pulverized-coal flame was investigated. Based on the correlation, it was expected that prediction of the practical flame structure would be possible to some degree.

1. Introduction

Coal is the most abundant and widely distributed fossil fuel in the world. The International Energy Agency (IEA) has estimated that coal will be available for over 120 years, with coal reserves of close to 800 billion tons [1]. However, for many of the countries that import most of their coal, including Korea, fuel-type diversification is inevitable because of the rising price of coal and the imbalance between supply and demand with increasing coal consumption. Therefore, the usage of low-rank coals in power plants is expected to increase further. One of the most probable solutions for realizing the use of low-quality coals is blending. The use of coal blends is becoming increasingly common in pulverized-coal power plants because it improves the economic performance of these plants by diversifying the fuel range. Moreover, although blending can improve combustion behaviors, decrease gaseous pollutant emissions, and mitigate operation problems (e.g., ash deposition), it does not always mitigate operation problems in terms of grinding, flame stability, heat absorption balance, ash deposition, etc., especially when a low-rank coal is blended. A blended product that closely resembles the design coal specifications may not burn in the same way as single coals do. Interactions can occur between the component coals, which may or may not be beneficial [2,3]. Thus, the compatibility of alternate coals with respect to their combustion performances has to be properly evaluated.

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Research involving thermal analysis has been conducted in the past to investigate combustion processes and thermal characteristics such as ignition and burnout of various coals [4–13]. Moreover, much research has been conducted to evaluate the interactions between parent coals and their blends using diverse methods with laboratory devices and pilot-scale experimental devices, because it is quite difficult to define the combustion behavior based exclusively on the thermal analysis of blended coals. Su et al. investigated the ignition characteristics, flame stability, and combustion conversion rate of blended coals using thermogravimetric analysis (TGA) and a drop tube furnace (DTF) in the laboratory-, pilot-, and full-scale facilities [14]. Biswas et al. conducted experimental studies involving TGA and DTF to investigate the combustion behaviors of blends of the same rank having wide variations in mineral matter content [15]. Artos and Scaroni researched the combustion characteristics of blends on the basis of their pyrolysis values and combustion efficiencies and showed that the blending of high- and low-rank coals did not affect the combustion behaviors of the component coals in TGA or a drop tube reactor (DTR) [16]. The ignition behaviors of pulverized coals and their blends were investigated using a flame-monitoring technique with the derivative thermogravimetric (DTG) evolution profile and gas distribution in an entrained flow furnace [17,18]. Additionally, pulverized coal burnout in the blast furnace was tested with various coals and coal blends [19].

Nevertheless, this was insufficient to predict the combustion behaviors of blended coals because previous studies on blends have shown different results for different types of coals and experimental methods. Moreover, practices have shown that the behaviors of blended coals do not always comply with the expected weighted average values based on the parameters of the pure coals constituting the blend. If flame ignition occurs in a furnace, the flame is propagated even in a low-rank coal condition, which makes ignition and flame stabilization an interesting issue in the coal blending application. Therefore, it is still indispensable to investigate the thermal conversion and flame characteristics of blended coals, including various low-rank coals.

In this research, the effects of the properties of coal on its thermal and combustion behaviors were studied using thermal analytical methods. Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) were used to evaluate the thermal evolution profiles that occurred during the process. The characteristic parameters of each sample, including the ignition and burnout temperatures and the combustion rate, were investigated during the pyrolysis process to indentify the thermal properties in the thermal evolution profile of blended coal. Thermal analytical methods such as TGA and DTA have been shown to be effective tools for providing fundamental information about the combustion behavior of coal. Various combustion characteristics can be obtained from TGA and DTA profiles, and these are partially reflected in the practical system. However, further consideration is necessary to apply the combustion characteristics obtained from the thermal analysis of a practical system, because the operating conditions, especially the heating rate, are very different between a thermogravimetric analyzer and practical system.

Therefore, the combustion characteristics of coals of different ranks in a laboratory-scale slit burner, which accurately represents the practical conditions of a flame with a high heating rate and jet velocity, were also studied. Combustion characteristics such as the mean flame temperature and combustion region were investigated using the chemiluminescence intensity distribution and intensity ratio of CH^* and C_2^* at upstream of the pulverized-coal flame. Finally, the correlations between the results of two different experiments, using thermal analysis and the laboratory-scale slit burner, were investigated. These experiments used a high-quality bituminous coal, Moolarben, which is a type of high-rank coal from Australia, and two low-quality sub-bituminous coals, Openblue and Wara, which are low-rank coals from Indonesia, along with blends of these coals.

2. Experimental

2.1. Materials

Five coal samples—two types of low-rank coals (Openblue and Wara) from Indonesia, a high-rank coal (Moolarben) from Australia, and their blends (M + O and M + W)—were used in this study. Each sample was milled and sieved to the desired particle size (around 75 μm), and the blending ratio based on the mass fraction was 1:1. These samples were used directly in a laboratory-scale experiment, thermogravimetry analyzer, and slit burner, without any moisture treatment, and the results of the proximate and ultimate analyses, as well as the calorific values, of each coal sample are listed in Table 1.

2.2. Thermogravimetric and differential thermal analysis

The weight loss of the sample and the rate of the weight loss were recorded continuously under dynamic conditions as functions of time or temperature, and all the experiments were performed at atmospheric pressure, under an inert air atmosphere with a flow rate of 100 mL/min using a TG-differential scanning calorimetry (DSC) instrument (SDT Q600, TA instruments). The samples under test were uniformly spread and initial weights of 25 ± 1 mg were selected to reduce the effects of side reactions and mass and heat transfer limitations. The temperature was increased from ambient to 800 °C at a heating rate of 10 °C/min and was held constant at this value until steady conditions were reached. The experiments were replicated at least five times to determine their reproducibility. The characteristic temperature differences of each sample were ±3 °C (±1%), and the weight loss rates were almost the same. Further, TG/DTG/DTA profiles exhibited the same tendency during the experiments.

2.3. Laboratory-scale combustion apparatus and optical measurements

Fig. 1 shows a schematic diagram of a pulverized-coal combustion system with an annular slit burner and a fuel-supply system. The burner had a coaxial dual piping structure with a main burner port (inner diameter: 6 mm) and an annular slit burner (width: 0.5 mm) installed outside the main burner port. In this study, pulverized-coal particles supplied and regulated by a screw-type

Table 1
Proximate and ultimate analyses of sample coals.

Coal type	Proximate analysis (wt%, air dry basis)				Ultimate analysis (wt%, dry basis)					Caloric value (MJ/kg)
	M	VM	FC	Ash	C	H	O	N	S	
Moolarben	4.25	28.32	51.89	15.54	64.7	4.53	13.52	0.75	0.3	25.8
Openblue	26	37.6	34.31	2.1	62.3	4.93	18.32	2.94	0.24	15.4
Wara	30.54	34.41	32.32	2.83	70.8	5.11	20.48	1.1	0.18	17.2