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Experimental study on interaction and excess heat release under oxy-fuel combustion of blended coals

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Abstract−The combustion behavior and excess heat release during the oxy-fuel combustion of blended coals were investigated experimentally using a non-isothermal thermogravimetric analyzer. The atmospheres were set to 10%O_2/90%CO_2, 21%O_2/79%N_2, 30%O_2/70%CO_2, and 50%O_2/50%CO_2, and Arthur coal (bituminous coal, BA) and KPU (sub-bituminous coal, SK) were selected as fuel with blending ratios of BA25%/SK75%, BA50%/SK50%, and BA75%/SK25%. The purpose of this study is to investigate the interaction between the blended coals and the effects of blending ratio and oxygen concentration on the excess heat release under oxy-fuel combustion. The results showed that as the oxygen concentration and proportion of sub-bituminous coal increased, the peak value in the differential thermal analysis curve increased by the enhanced reaction rate. A higher oxygen concentration led to excess heat release. The ignition temperatures depended on the volatile matter content of the sub-bituminous coal, whereas the burnout temperature was largely affected by the fixed carbon content of the bituminous coal. For interaction behaviors on characteristic temperatures, the volatile release temperature shows an additive behavior; however, ignition and burnout temperatures show non-additive behaviors for blended coals.

Key words: Blended Coals, Interactions, Excess Heat Release, Oxy-fuel Combustion

INTRODUCTION

In pulverized coal thermal power plants, the use of coal types beyond the scope of the design is inevitable because the imbalance between coal demand and supply has become serious owing to the increasing energy consumption by large countries such as China and India. The importance of blended coals with bituminous and sub-bituminous components is being emphasized as promising for using low-rank coals. Coal blending is effective for improving the combustion performance, meeting pollutant emission limits, controlling ash deposition, extending the range of acceptable coals, and reducing the coal cost [1]. On the other hand, carbon dioxide (CO_2) emissions from pulverized coal thermal power plants are very high, and their effect on global climate change has been acknowledged worldwide. Moreover, the reduction of CO_2 is compulsory owing to political regulations of the Kyoto protocol and the Intergovernmental Panel on Climate Change (IPCC). As an alternative, oxy-fuel combustion is considered as promising in terms of carbon capture and storage. Oxy-fuel combustion systems have a natural advantage in retrofitting existing pulverized coal power plants because they can reuse most of the existing plant equipment [2]. Therefore, co-firing of high- and low-rank coal under oxy-fuel combustion is suggested as an alternative method for addressing both economic and environmental issues.

The combustion behavior of coals depends on the coal properties such as volatile matter, ash content, surface area and active sites, the minerals in the ash, and rank of coals; it also depends on the combustion conditions such as temperature, heating rate, and oxygen concentration [3]. Su et al. provided an extensive review of techniques for determining the parameters that affected blended coal; they focused on the ignition characteristics, flame stability, and carbon burnout rate [4]. Nugroho et al. investigated the dependence of the ignition characteristics and activation energy on the particle size of single and blended coals and the physical structure of the coal particle [5]. Chi et al. introduced flame monitoring to investigate the ignition behavior of seven different pulverized coals and coal blends in a drop tube furnace (DTF) [6]. The coal property parameters such as heating value and proximate and ultimate analysis data of blended coals are known as additive behaviors [1]. However, some properties in terms of NO_x emissions, carbon burnout and ash fusion temperature, which is related to the phenomena of slagging and fouling, may not be easily inferred by the additivity method or by empirical relations [7]. Artos and Scaroni showed that the combustion efficiencies of the blends were linearly predictable from the combustion efficiencies of the individual coals that they contained [8]. However, Arenillas et al. argued that it was impossible to predict the combustion characteristics of blends from the properties of individual coals [9].

Buhre et al. provided a summary of oxy-fuel combustion in terms of four issues (heat transfer, environmental issues, ash-related issues, and combustion characteristics) [10]. Toftegaard et al. discussed retrofit technology for oxy-fuel combustion and the fundamental combustion characteristics, including heat transfer effects, ignition and burnout, emissions, ash quality, and deposit build-up [11]. Many researchers have studied the characteristics of oxy-fuel combustion

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Table 1. Proximate and ultimate analysis of coal samples

Coal	Proximate analysis (wt%, air-dry)				Ultimate analysis (wt%, dry)						HHV[d] (MJ/kg, air-dry)
	M[a]	VM[b]	FC[c]	Ash	C	H	O	N	S	Ash	
BA[e]	0.15	35.96	41.07	22.82	70.2	5.09	5.87	1.71	0.97	16.16	27.69
SK[f]	11.3	45.27	34.84	8.59	66.6	5.77	18.87	1.19	0.07	7.5	22.68

[a]M: moisture
[b]VM: volatile matter
[c]FC: fixed carbon
[d]HHV: high heating value
[e]BA: Australian bituminous coal; Arthur
[f]SK: Indonesian sub-bituminous coal; KPU

using laboratory-scale equipment such as a thermogravimetric analyzer (TGA) and DTF [12-17]. Recently, several studies have reported the combustion characteristics of co-firing with coal and biomass under oxy-fuel combustion conditions [18-21].

The burning of coal in a pure-oxygen or oxygen-enriched atmosphere is typically applied to high-temperature processes, such as the excess heat resulting from enhanced particle temperature in the combustion chamber during the devolatilization process and char combustion. Many researchers have reported that the average particle temperatures increase when the oxygen concentration is increased beyond that of atmospheric conditions [22-25]. The excess heat released from oxy-fuel combustion may cause the formation of NO_x and damage the equipment, although it may enhance the combustion reaction and improve the flame stability. A detailed understanding of the excess heat released from oxy-fuel combustion could provide useful information for predicting the flame-radiant region and burning characteristics.

In particular, there has been relatively insufficient research on the combustion characteristics of blended coals with bituminous and sub-bituminous coals under oxy-fuel combustion conditions. A number of laboratory TGA techniques have been widely used to study the pyrolysis and combustion characteristics of coal and to evaluate the relative burning properties of coal samples [26-31]. Although extrapolation to other devices at a larger scale cannot be performed directly, the information obtained from the combustion profiles in thermogravimetry (TG) could be used for an initial evaluation of the behavior of the combustion on an industrial scale [32].

In this study, two types of coal used in pulverized coal power plants were chosen to investigate the combustion characteristics of blended coals with bituminous and sub-bituminous components under oxy-fuel combustion conditions. The effects of oxygen concentration and blending ratio on excess heat release under oxy-fuel combustion were investigated experimentally using a TGA. The excess heat was defined as excessive heat released by an oxidizing reaction between coal and oxygen than programmed temperature profile of the TGA. To investigate the effects of the oxygen concentration of fuel and oxidizer on excess heat release, the total oxygen concentration was defined as the sum of the fuel oxygen (ultimate analysis) and the oxidizing oxygen (purge gases). The characteristic temperatures, including the volatile release, ignition, and burnout temperatures, were determined from TG and derivative thermogravimetry (DTG) curves. The purpose of this study is to provide fundamental information for predicting the combustion behavior of blended coals under various operational conditions and relationship between oxygen concentration and excess heat release.

EXPERIMENTAL SECTION

Two parent coals, an Australian bituminous coal, Arthur (BA), and an Indonesian sub-bituminous coal, KPU (SK), were selected as fuel, and their blends (BA75%/SK25%, BA50%/SK50%, and BA25%/SK75%) were also considered. The raw coal sample was first crushed and pulverized using a bench-scale mill in the laboratory and then sieved on a screen vibrator. The proximate and ultimate analyses of the samples are summarized in Table 1.

Temperature-programmed combustion tests were performed in a themogravimetric apparatus (TA Instrument SDTQ600). Approximately 20 mg of each sample (45-75 µm in diameter) was heated at 10 K/min from ambient temperature to 1,173 K, with a flow rate of 100 mL/min for air or for a mixture of O_2/CO_2. The atmospheres used were $10\%O_2/90\%CO_2$ (oxy 10%), $21\%O_2/79\%N_2$ (air), $30\%O_2/70\%CO_2$ (oxy 30%), and $50\%O_2/50\%CO_2$ (oxy 50%).

During the TGA, the mass loss, time, and temperature histories were recorded simultaneously; these values were used to produce the combustion history including TG, DTG, and differential thermal analysis (DTA) curves. DTA provides qualitative information on the energy of the heat release related to the reaction process. From combustion history, the characteristic parameters, including the vol-

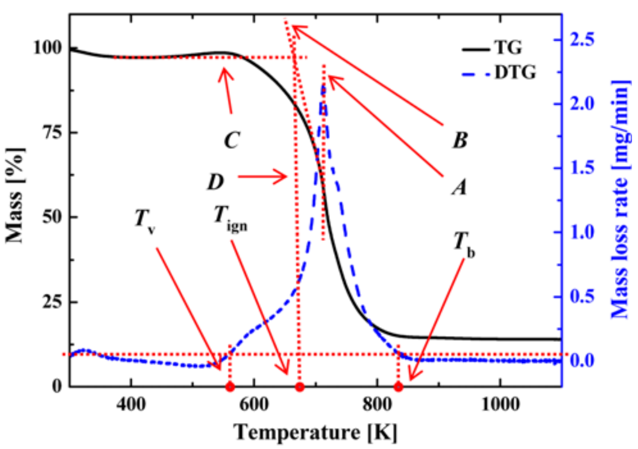

Fig. 1. Definitions of characteristic temperatures from TG and DTG combustion profiles.

Table 2. Characteristic temperatures of coals BA and SK and their blends, and comparison between experimental and theoretical (weighted average) values under different atmospheres

Atmosphere	Sample	T_v (Theoretical) [K]	T_{ign} (Theoretical) [K]	T_b (Theoretical) [K]
Oxy 10%	BA	599	682	884
	BA75/SK25	581 (583)	654 (661)	877 (863)
	BA50/SK50	560 (567)	612 (641)	870 (841)
	BA25/SK75	545 (551)	606 (620)	851 (820)
	SK	535	599	798
Air	BA	582	662	832
	BA75/SK25	562 (569)	628 (641)	828 (802)
	BA50/SK50	546 (555)	610 (620)	828 (772)
	BA25/SK75	538 (542)	601 (599)	813 (741)
	SK	528	578	711
Oxy 30%	BA	568	637	821
	BA75/SK25	549 (555)	607 (610)	812 (786)
	BA50/SK50	530 (542)	547 (584)	807 (751)
	BA25/SK75	518 (528)	532 (557)	793 (715)
	SK	515	530	680
Oxy 50%	BA	549	625	805
	BA75/SK25	538 (538)	553 (598)	797 (755)
	BA50/SK50	524 (527)	533 (571)	788 (705)
	BA25/SK75	511 (516)	519 (544)	781 (655)
	SK	505	517	605

Notes: T_v is the volatile release temperature, T_{ign} is the ignition temperature, T_b is the burnout temperature

atile release temperature (T_v), ignition temperature (T_{ign}), and burnout temperature (T_b), were obtained to characterize the combustion characteristics. These parameters may reflect the thermal behavior of the coal organic matter during the combustion and help identify the end of combustion and combustion reactivity. As shown in Fig. 1, T_v was defined as the temperature at which the DTG profile reaches 0.1%/min after the initial moisture removal [8,33]. T_{ign} was defined as follows [34,35]: first, a vertical line **A** passing through the DTG peak point was extended downward to meet the TG curve at a point; second, a tangent line **B** was drawn for the TG curve at the point of intersection between line **A** and the curve. Another vertical line was extended downward from the point of intersection of lines **B** and **C**, corresponding to T_{ign}. T_b was defined as the temperature at which the DTG profile was reduced to 0.1%/min at the end of the profile [8]. Table 2 shows the characteristic temperatures of coals BA and SK and their blends, and comparison between the experimental and theoretical (weighted average) values under different atmospheres.

To investigate the effect of the total oxygen concentration on the heat release distribution, the total oxygen concentration (O_t) was defined as the sum of the fuel oxygen (O_f) in ultimate analysis and the oxidizing oxygen (O_o) in purge gases. Assuming no interaction between the bituminous and sub-bituminous coal when two samples are blended, the major properties of the blended coals, such as the calorific value, total moisture, volatile matter, fixed carbon, ash, and absolute C, H, O, N, and S content in the ultimate analysis, may be calculated by the weighted average of the values for the individual coals [7]. Thus, the values of O_f can be obtained from the weight proportion of the blended coals. Table 3 shows the values for O_f, O_o, O_t, and the peak DTA value that represents the peak energy of the heat release under each experimental condition.

RESULTS AND DISCUSSION

1. Combustion Characteristics for Single Coal with Oxygen Concentration

Fig. 2 shows the TG, DTG, and DTA curves for the single coals with different oxygen concentrations. The mass loss process of coal samples can be divided into three major stages: the moisture evaporation stage, which is not included in the burning-profile characterization; the reaction region stage, for volatile matter and char; and the burnout region stage, for char. It is evident from the TG, DTG, and DTA profiles that the oxygen concentration does not affect the moisture-removal process and the ash decomposition. However, in the reaction region of the volatile matter and char, significant mass loss was observed with increasing oxygen concentration. As shown in Figs. 2(a), (b) and 2(c), (d), which are the TG and DTG curves, respectively, the mass loss of coal SK occurs clearly at lower temperatures than the temperature at which mass loss at coal BA occurs. This is mainly because of the relatively high volatile matter and less fixed carbon content in coal SK, which makes the combustion reactivity of coal SK better than that of coal BA. The mass loss processes of the different atmospheres (oxy 10%, oxy 30%, and oxy 50%) can be easily distinguished as two different curves of low oxygen and high oxygen concentration. As expected, the increased oxygen concentration shifted the TG curves to a low temperature, and the DTG peak value indicated that the maximum mass loss was proportional to the oxygen concentration regardless of the types of coal. A higher oxygen concentration might enhance the volatile release and combustion reaction of coal samples.

Table 3. Summary of the exothermic heat release for different total oxygen concentrations - peak DTA

Atmosphere	Sample	O_f [%]	O_o [%]	O_t [%, O_f+O_o]	Peak DTA [μV]
Oxy 10%	BA	5.87	10	15.87	101.73
	BA75/SK25	9.12	10	19.12	107.86
	BA50/SK50	12.37	10	22.37	140.34
	BA25/SK75	15.61	10	25.61	158.11
	SK	18.86	10	28.86	161.76
Air	BA	5.87	21	26.87	176.66
	BA75/SK25	9.12	21	30.12	127.69
	BA50/SK50	12.37	21	33.37	245.19
	BA25/SK75	15.61	21	36.61	239.71
	SK	18.86	21	39.86	306.28
Oxy 30%	BA	5.87	30	35.87	287.67
	BA75/SK25	9.12	30	39.12	341.68
	BA50/SK50	12.37	30	42.37	418.81
	BA25/SK75	15.61	30	45.61	517.06
	SK	18.86	30	48.86	546.50
Oxy 50%	BA	5.87	50	55.87	525.50
	BA75/SK25	9.12	50	59.12	502.23
	BA50/SK50	12.37	50	62.37	673.13
	BA25/SK75	15.61	50	65.61	833.31
	SK	18.86	50	68.86	796.61

Notes: O_f is the fuel oxygen concentration, O_o is oxidizing oxygen concentration, O_t is total oxygen concentration

In Figs. 2(a) and 2(b), temperature drops are observed from 690 to 720 K for coal BA in the oxy 50% atmosphere, and from 560 to 640 K for coal SK in air, oxy 30%, and oxy 50% atmospheres. This temperature tended to shift toward a low temperature as the oxygen concentration increased. The excess heat release during combustion of the fuels at high oxygen concentrations caused a large temperature difference between the burning coal and the furnace in TGA. That is, the temperature of the coal particles drops until it reaches the programmed furnace temperature, as seen in the TG curves, because the coal particles are exposed to higher temperatures than those in the furnace [21]. This behavior becomes more easily explainable when mass loss and temperature are plotted versus time, as shown in Fig. 3. A sudden mass loss as well as a large spike accompanies this event. The spike of coal SK was higher than that of coal BA, and progressively increased as the oxygen concentration increased. The sample started burning and released a considerable amount of heat very quickly, causing a sharp increase in the temperature followed by heat dissipation and a subsequent temperature drop [36]. Cho et al. reported that the heat obtained from the burning of volatiles was fed back to the coal-particle surface, further increasing the coal-particle temperature and devolatilization rate [37]. Bejarano and Lavendis also observed that as the oxygen mole fraction in the furnace increased, the particle temperatures increased, reducing the burnout durations [38]. At a furnace temperature of 1,500 K, the average char temperatures were recorded as 1,800 K in air, 2,300 K in 50% oxygen, and 2,400 K in 100% oxygen [38]. Even though the heating rate of TGA is significantly lower compared with the practical furnace, the excess heat may affect the thermal distribution in the furnace.

As shown in Figs. 2(e) and 2(f), the DTA curves started with small endothermic regions resulting from the moisture removal for both coals, and the main burning region for the volatile and char reaction then followed with a release of heat. As shown in Fig. 2(e), the heat release exothermic curves for coal BA showed two distinguishable peaks, for volatile and char combustion. The second peak

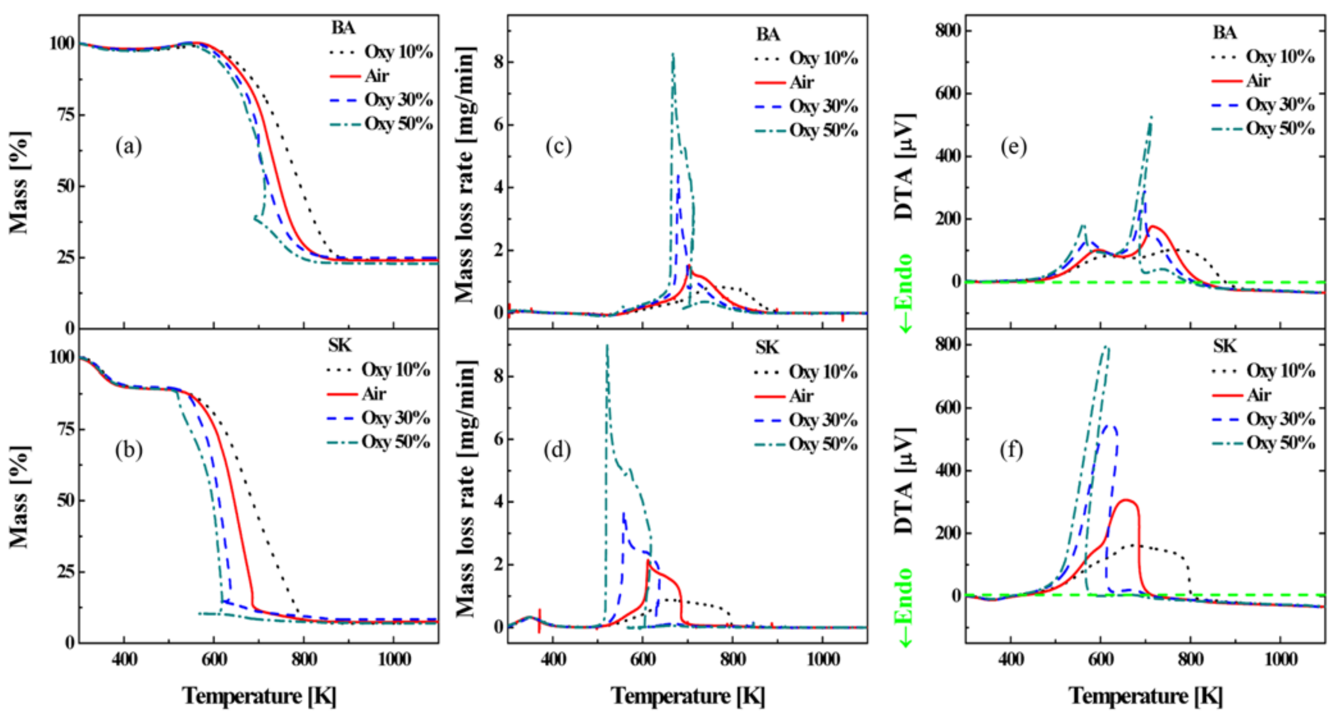

Fig. 2. TG, DTG, and DTA curves for coals BA and SK under different atmospheres.

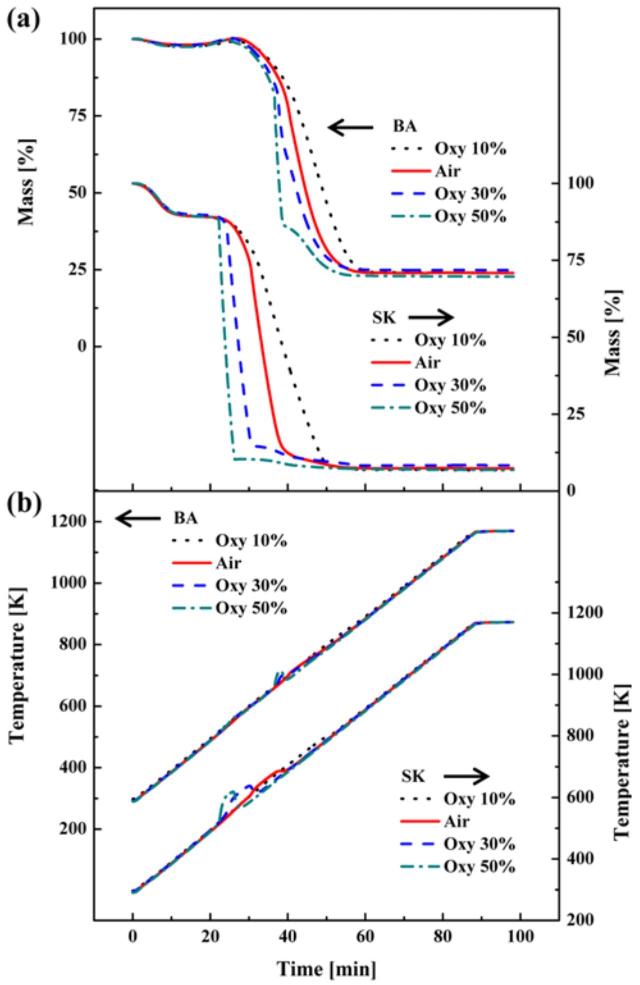

Fig. 3. Mass trace and temperature versus time for coals BA and SK under different atmospheres.

of the char combustion is higher than the first peak, and two peaks show very high and sharp shapes with increasing oxygen concentration. For coal SK, the one peak corresponding to the volatile and char combustion is shifted to the low temperature zone with an increase in oxygen concentration. Namely, the heat release pattern with the oxygen concentration is quite different for both samples. Three different mechanisms of coal particle ignition explain these DTA behaviors: homogeneous, heterogeneous, or hetero-homogeneous combined ignitions. For homogeneous and heterogeneous ignitions, two exothermic peaks and only one strong exothermic peak appear, respectively [14]. Coal SK shows relatively higher heat release than coal BA. The peak DTA values, which indicate peak heat release, were 833 µV at 610 K for oxy 50%, 547 µV at 620 K for oxy 30%, 306 µV at 660 K for air, and 162 µV at 670 K for oxy 10%, as shown in Table 3. That is, the excess heat release of the coal combustion is proportional to the oxygen concentration, and the exothermic regions show sharp peaks owing to high heat release rates.

2. Combustion Characteristics of Blended Coals in Oxy-fuel Condition

Fig. 4 shows the effects of the oxidizing conditions on the thermal behaviors of coals BA and SK and their blends. From the TG and DTG curves, the mass loss processes of the blended coals (BA75/SK25, BA50/SK50, and BA25/SK75) are shifted to a lower temperature zone between coals BA and SK, mainly because of the higher volatile contents of blended coal than coal BA. Coals containing a large amount of volatile matter are easy to ignite and burn quickly owing to the easy release of volatile matter. There was a clear improvement in the devolatilization characteristics for the blended coal with the presence of coal SK.

Moreover, the presence of coal SK led to improvements in the conversion yields. In all cases, the final mass of the coal samples was almost identical, regardless of the oxygen concentration, as shown in Figs. 4(a)-(d). The residual masses of BA75/SK25, BA50/SK50, and BA25/SK75 wt% were 19.58, 15.5, and 12.06 wt%, respectively, whereas the final mass of coal BA was 23.85 wt% of the initial mass. These reductions in the final mass are proportional to the percentage of coal SK in the blend. The final mass during co-combustion follows a linear function of the blending ratio with respect to the ash contents of the individual coals. Basically, ash is an inert material and does not participate in the combustion process [33]. Compared with bituminous coal combustion, the combustion of blended bituminous and sub-bituminous coals can assist in ash reducing the ash in coal-fired thermal power plants.

The excess heat release was also observed in blended coals. It appeared from 560 to 700 K in oxy 30% and oxy 50% atmospheres. From Fig. 4(d), the excess heat for pure SK, BA25/SK75, BA50/SK50, and BA75/SK25 was observed at around 600 K, and the position of the excess heat release shifted to the end of the main reaction region with an incremental increase in SK blending. The excess heat was not observed in coal BA in oxy 10% and air atmospheres. However, as shown in Figs. 4(c) and 3(d), the excess heat occurred at the relatively high oxygen concentration of even pure coal BA. The excess heat phenomenon moved to the end of the main reaction region and increased in magnitude by increasing the oxygen concentration and coal SK blending ratio. Figs. 4(i)-(*l*) show the DTA curves corresponding to the combustion of blended coals under different atmospheres. From coal BA, with an increase in the coal SK blending ratio, the first peak corresponding to the volatile combustion increased while the second peak corresponding to the char combustion decreased. This may be due to a difference in the indigenous properties between coals BA and SK, and the interaction of the individual coals. This behavior became significant, and the DTA value was enhanced by increasing oxygen concentration. That is, the heat release pattern changes with the increase in the coal SK blending ratio and oxygen concentration for blended coals. From these results, the tendency of the effects of oxygen concentration and blending ratio on the radiation region in a practical furnace can be predicted.

Fig. 5 shows the value of peak DTA, which represents the peak energy of the heat release with total oxygen concentration. The heat release is proportional to the oxygen concentration because the oxidation reaction rate is a function of oxygen concentration. A higher oxygen concentration for purge gas and the presence of coal SK, which included relatively higher oxygen content in the ultimate analysis, led to a substantial release of excess heat. Haykiri-Acma suggested that coal combustion with a high oxygen concentration could be controlled by blending coal with biomass in the ratios of 5-20 wt% [21]. The flame temperature of the oxy-fuel condition can be

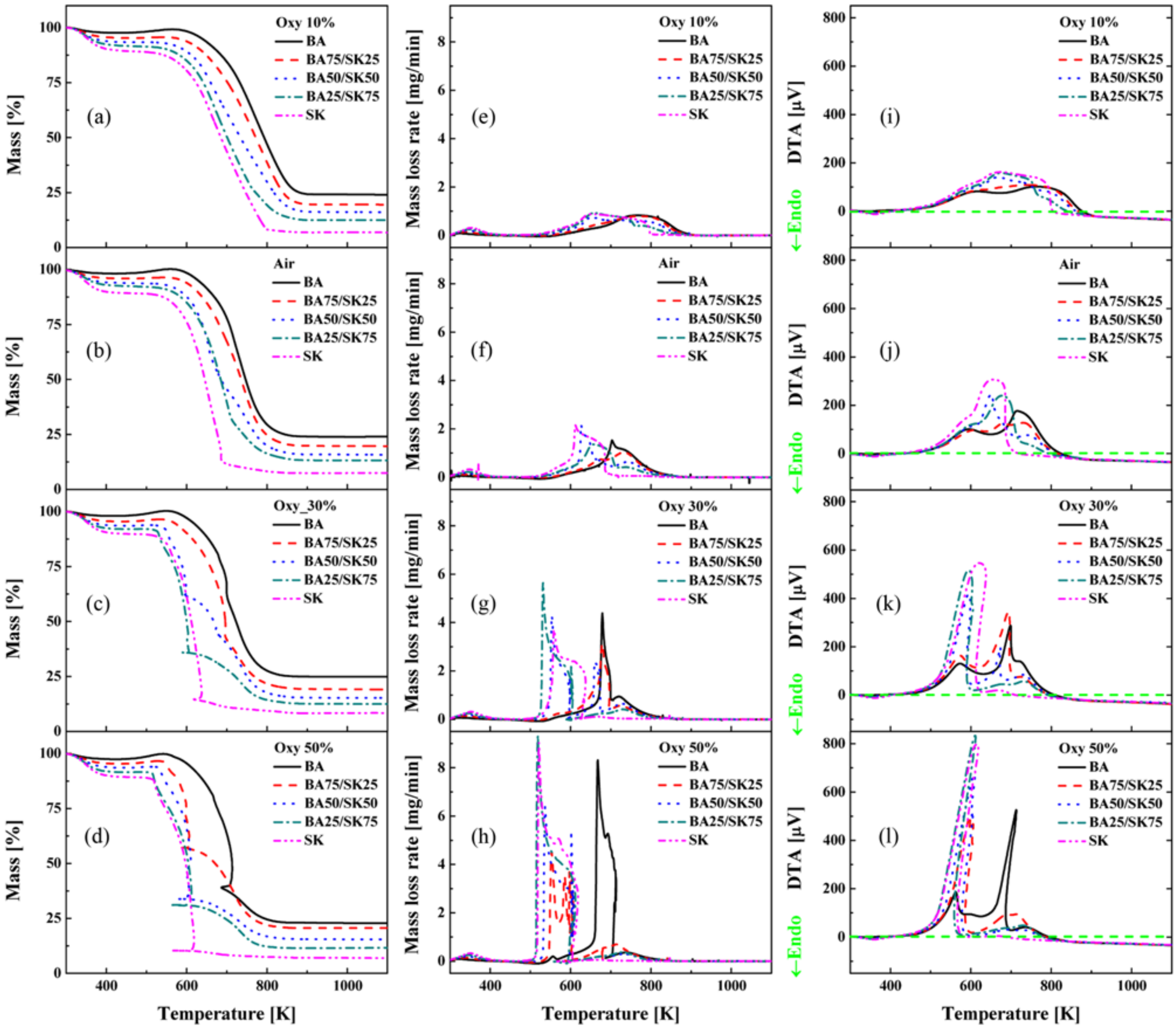

Fig. 4. TG, DTG, and DTA curves for coals BA and SK and their blends under different atmospheres.

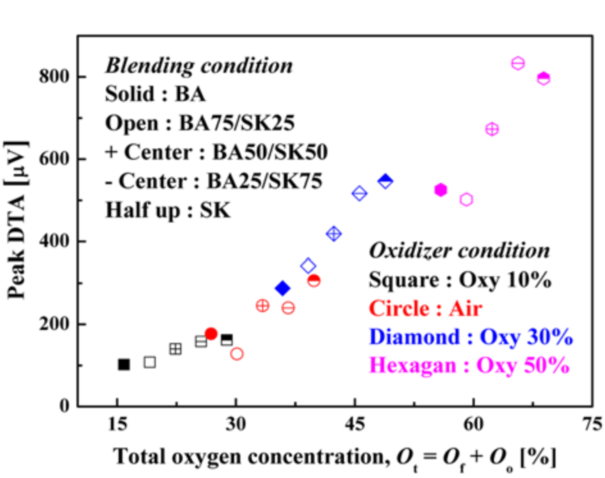

Fig. 5. Linear relationship between the peak excess heat release and total oxygen concentration for fuel and oxidizing oxygen. O_t: total oxygen concentration (O_f+O_o), O_f: fuel oxygen concentration based on the ultimate analysis, O_o: oxidizing oxygen concentration.

increased by blending fuel with high oxygen concentrations. The high exothermic reaction resulting from the combustion of oxy-fuel should be controlled by considering fuel containing oxygen as well as the oxidizer oxygen concentration because the total oxygen concentration significantly affects heat release.

3. Effects of Blending Ratio and Oxygen Concentration on Characteristic Temperature

Fig. 6 and Table 2 show the volatile release (T_v), ignition (T_{ign}), and burnout (T_b) temperature distributions of coals BA and SK and their blends, and a comparison between experimental and theoretical (weighted average) values under different atmospheres. From Fig. 6(a), T_v decreased with increasing coal SK blending ratio. In the air atmosphere, as shown in Table 2, T_v for coal SK (528 K) was much less compared to coal BA (582 K), and similar results were observed under other oxidizer conditions. The mass loss started at a low temperature as coal SK increased, as shown in Fig. 4. This phenomenon was ascribed to the enhancement of devolatilization by blending with coal SK. Sub-bituminous coal blending may enhance the devolatilization characteristics owing to higher volatile

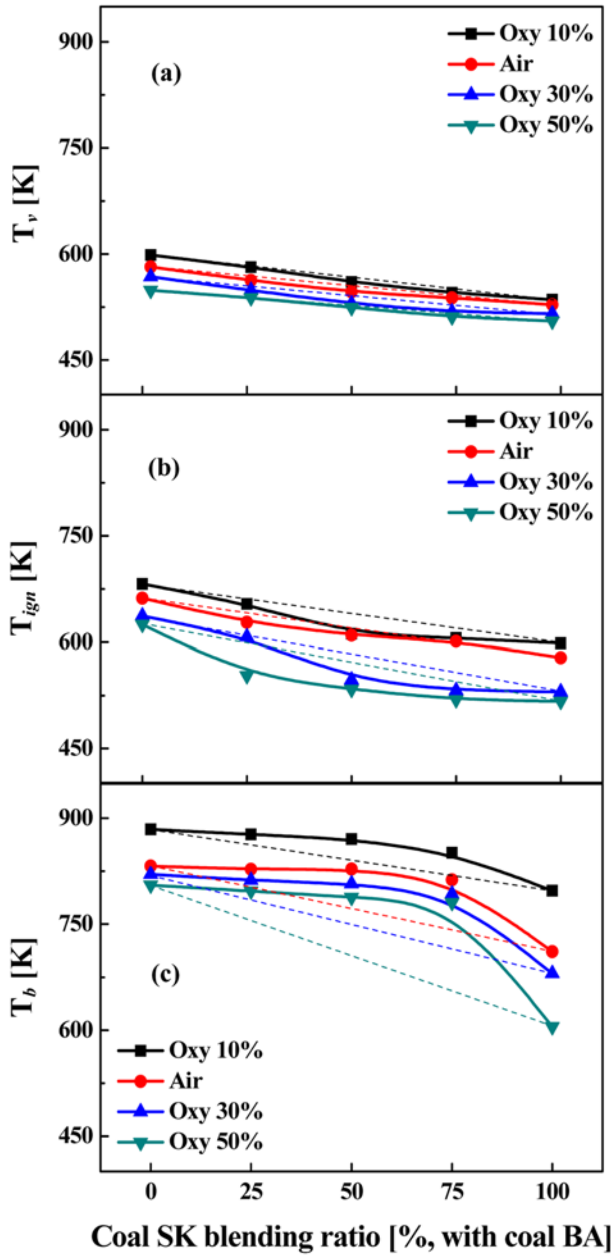

Fig. 6. Volatile release (T_v), ignition (T_{ign}), and burnout (T_b) temperature distributions of coals BA and SK and their blends under different atmospheres (dotted lines: weighted average values).

matter. This is because the volatile matter of sub-bituminous coal is released early at a lower temperature than that of bituminous coal. Volatile matter content seems to be a very important factor to T_v. T_v also decreased as the oxygen concentration increased. A higher oxygen concentration may further enhance the devolatilization of blended coals. No obvious deviations are observed between the experimental and calculated T_v values of blended coals. Thus, there are no significant interactions, and hence, there exists the additive behavior of blended coals.

Fig. 6(b) shows the ignition temperature (T_{ign}) distributions of coals BA and SK and their blends under different atmospheres. It is clear that as the oxygen concentration and coal SK blending ratio increased, T_{ign} gradually decreased. T_{ign} was inversely proportional to the amount of coal SK in the blend. The lower T_{ign} resulted from the increase in the volatile-matter content of the coal particles. Sub-bituminous coal blending helps initiate the ignition of coal particles. Similar results have been found when blending high- with low-rank fuel [28,30,33]. The measured T_{ign} was lower than the weighted average prediction (dotted lines) of the temperature under all blending conditions.

Fig. 6(c) shows the burnout temperature (T_b) distributions of coals BA and SK and their blends under different atmospheres. The maximum and minimum burnout temperatures were 884 K in oxy 10% for coal BA and 605.2 K in oxy 50% for coal SK, respectively. As the oxygen concentration and the presence of sub-bituminous coal increased, T_b decreased. In contrast to T_{ign}, the measured T_b was higher than the weighted average prediction (dotted lines) of the temperature under all blending conditions. Although T_{ign} depends on the volatile content of the sub-bituminous coal in oxy-fuel combustion as well as in air combustion, T_b is seriously affected by the fixed carbon content of the bituminous coal. Therefore, the presence of bituminous coal in a blend has a significant effect on T_b. According to the results of the ignition and burnout characteristics, it is expected that the addition of low-rank coals can improve ignition characteristics and reduce the burning time of blended coals. Another expectation is that the ignition characteristics of blended coals is closer to that of low-rank coal, and the burnout characteristics of blended coals are closer to that of high-rank coal. According to the results in Figs. 6(b) and 6(c) and Table 2, no additive behavior of blended coals was observed. In particular, the burnout temperature showed significant interactions between coals BA and SK, and hence, significant synergetic effects exist during the co-firing process.

CONCLUSIONS

To understand the combustion characteristics of blended coal fuel under oxy-fuel conditions, the effects of the blending ratio and oxygen concentration on the combustion characteristics were investigated through a TGA experiment. The main results can be summarized as follows:

1) The excess heat release of the coal combustion was proportional to the oxygen concentration, and the exothermic regions showed sharp peaks owing to high heat release rates. The heat release pattern changes with the addition of low-rank coal and the increase in oxygen concentration.

2) A linear relationship was observed between the value of peak DTA, which represents the peak energy of the heat release, and total oxygen concentration.

3) For the interaction behaviors on characteristic temperatures, the volatile release temperature indicates an additive behavior; however, the ignition and burnout temperatures show non-additive behavior for blended coals. The ignition temperature was greatly affected by the volatile matter and oxygen concentration, and the burnout temperature depended on the fixed carbon content of the coal fuel.

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