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Research article

Regulation of ash-fusion behaviors for high ash-fusion-temperature coal by coal blending

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ABSTRACT

Blending is a promising method to modify the ash-fusion characteristics of coal to meet gasification requirements. To investigate the variation in ash-fusion behavior for high ash-fusion-temperature (AFT) coal through coal blending and its regulating mechanism, the ash-chemistry characteristics of four coals (Nantun, Pengzhuang, Biaodian, and Xiangyuan) were analyzed. Mineral-transformation behaviors in the mixed ashes were investigated by X-ray powder diffractometry using normalized reference intensity ratio software, scanning electron microscopy analyzer equipped with energy-dispersive X-ray spectrometry, and FactSage software. Pengzhuang and Biaodian coals, AFTs meet entrained-flow gasifier requirements when the Xiangyuan mass ratio reaches 20%. The Nantun requires a Xiangyuan mass ratio of XY >30% because of its high aluminum oxide content. The required Xiangyuan optimal blending mass ratio is 40%–70% for the three high AFT coals to meet gasification requirements in the entrained-flow gasifier. An increased Xiangyuan mass ratio leads to decreasing contents of high melting-point mullite and silica and increasing contents of low melting-point anorthite, hercynite, gehlenite, and hedenbergite. Amorphous matter in three mixed ash types resulted in a decrease in their AFTs. The variation in liquid phase under certain conditions reflects the change in AFT.

1. Introduction

To relieve environmental stress (e.g., global warming, acid rain, air pollution, ozone depletion, and their influences on our ecosystem [1–3]), gasification technology, which converts coal into methanol, fuel oil, hydrogen, natural gas, and other chemical products, and IGCC plants [4], has gained attentions worldwide. Among three gasification technologies (fixed, fluidized, and entrained-flow), entrained-flow gasification with feedstock flexibility, a high efficiency, and a low environmental impact has become a promising development direction [5]. A key parameter during coal gasification in entrained-flow is to maintain smooth molten-slag tapping from the gasifier under specific operating temperatures [6]. The slag properties of fusibility flow and rheology during coal conversion (e.g., combustion and gasification) are related closely to the characteristics of slag viscosity and ash fusion temperature (AFT) [7–9]. To discharge slag from the entrained-flow gasifier continuously, the slag viscosity should range from 2.5–25 Pa·s at the operating temperature and the flow temperature (FT) must be below 1400 °C in a reducing atmosphere. Compared with the slag viscosity, some weaknesses (e.g., limited reproducibility, improper capture phenomena in entrained-flow gasifiers where ash is first subjected to high temperatures (as coal reacts), and then cooled as it impacts and runs down gasifier walls, and different mineral phase transformations during coal gasification because of ash heating) exist in AFT measurements. However, the AFT is still an accepted method to estimate the slagging propensity during coal entrained-flow gasification and to determine its minimum operating temperature (in general, more than its FT of 50 °C–100 °C) [10]. High-AFT coal (FT > 1400 °C) accounts for >57% of Chinese coal [11]. Therefore, it is of great importance to reduce the coal AFT for clean coal and to achieve high-efficiency conversion through entrained-flow gasification.

In general, the decrease in coal AFT is by flux-agent [12,13] and biomass addition [14], and by coal blending [15,16]. Flux agent is used widely in industry, but it consumes more oxygen and energy [4]. Biomass can decrease the coal AFT to some extent; however, it has a low energy density, high collection and drying cost, and a seasonal shortage [17]. Its higher reactivity compared with coal may lead to a two-stage reaction during co-gasification. Coal blending improves the ash viscosity–temperature characteristics, and is more efficient and economic because of complementary raw materials and an optimization of product structure [18]. Thus, it is necessary to explore variations in ash-fusion characteristics through coal blending.

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Table 1
Proximate and ultimate analyses of four coal samples.

	NT	PZ	BD	XY
Proximate analysis on air dry basis (wt%)				
Moisture	2.94	3.29	4.16	3.27
Volatile matter	34.55	27.18	36.84	28.19
Ash	9.74	11.52	10.38	26.15
Fixed carbon	53.77	57.38	51.38	42.49
Ultimate analysis on dry ash free basis (wt%)				
Carbon	76.75	84.81	78.26	82.57
Hydrogen	4.80	5.44	4.21	5.68
Nitrogen	1.43	1.46	1.37	1.23
Sulphur[a]	0.54	1.21	0.82	0.97
Oxygen[b]	16.48	7.08	15.34	9.55

[a] Total sulphur.
[b] From difference.

Table 2
AFTs of four coal samples under reducing atmosphere.

Samples	AFT[a,b]/°C			
	DT	ST	HT	FT
TN	1442	>1500	>1500	>1500
PZ	1340	1402	1427	1460
BD	1315	1392	1432	1448
XY	1104	1125	1153	1189

[a] AFT: ash fusion temperature; DT: deformation temperature; ST: softening temperature; HT: hemisphere temperature; FT: flow temperature.
[b] The standard deviations <5 °C.

The AFT variation behaviors of coal blending are affected mainly by ash chemical composition, blending ratio, and atmosphere [4], and are also related to pressure, because this impacts shifts in chemical equilibria among the various minerals. The relationships between the AFT variation in mixed ashes and blending ratio is non-linear [19,20]. The correlations between blending-ash compositions and their AFT have been investigated by support-vector machines and linear least squares [21,22]. The relationships between coal-blending AFT and its mineral factor, and their correlative mechanism have been explored [23,24]. The blending-coal experiments of Tianci and Xiaotun, Pingsuo and Shenhua show that content variations of mullite and anorthite in mixed ashes at a high temperature result mainly in their AFT variation [25,26]. The melting and reaction behaviors of main minerals in coal blending, and the AFT modification mechanisms were investigated by experimental testing and software (e.g., Gaussian and FactSage) [19, 27,28].

To reduce costs, low-quality coal (low heating value or high ash content) is sometimes used in industrial gasification. It is important to find an optimum blending ratio for high-ash-content coal (HAC) to meet the AFT requirement for entrained-flow gasification. Because of complexities in mineral compositions, transformations and interactions in blending coal, the modification behaviors of ash-fusion characteristics through coal blending are different. However, to our limited knowledge, papers on HAC as coal blending in gasification technology are still lacking. We investigated the influence of HAC addition on the AFT and explored the AFT modification mechanism. The results are expected to provide some guidelines for coal-blending gasification technology in an entrained-flow gasifier.

2. Experimental

2.1. Raw coal sample characteristics

Four air-dried coal samples were provided by the Coal Gasification Engineering Center in the Institute of Coal Chemistry, Chinese Academy of Sciences. Three samples (Nantun, Pengzhuang, and Biaodian coals) were from western Shandong, Eastern China and one sample (Xiangyuan coal) was from northern Hubei, Central China. The coal samples were crushed to <0.198 mm, and are referred to as NT, PZ, BD, and XY, respectively. Proximate analyses were conducted on a SDLA 718 proximate analyzer (SUNDY Co. Ltd., China), and ultimate analyses was performed on a PE 2400 analyzer (PerkinElmer, USA). The results are presented in Table 1. Table 2 provides the coal AFTs under reducing conditions of 50% carbon dioxide and 50% hydrogen (volume ratio) obtained from an ALHR-2 intelligent AFT analyzer (Aolian co. Ltd., China). The volatile matter contents of the four samples exceed 25%, and all belong to bitumite with a similar reactivity. The ash content of NT, BD, and PZ is relatively low (~10%), and exceeds 25% for XY (26.15%), which indicates that the sample is a typical HAC. The FTs of NT, PZ, and BD exceed 1400 °C (high-AFT coal) [29], whereas the FT (1189 °C) for XY is lower than 1200 °C, and belongs to a typical low-AFT coal.

2.2. Ash sample preparation

The preparation procedure for the 815 °C ash samples was as follows: XY was mixed with high-AFT NT, PZ and BD coals in a certain mass ratio (0, 10, 20, 30, 40, 50, 60, and 70 wt%) on an air-dried basis, respectively. The mixed samples were placed into a muffle furnace, and were ashed according to Chinese standard procedures (GB/T1574-2001). The mixed ashes were crushed to <75 μm for AFT tests and further analysis.

Ash samples were analyzed in the AFT analyzer at different preset temperatures under a reducing atmosphere [30]. After the preset temperature had been reached, ash samples in the AFT analyzer were transferred immediately into ice water to prevent crystal segregation and phase variation. Quenched ash samples were placed into a vacuum drying chamber and kept at 105 °C for 24 h, and then they were stored in a drying closet before measurement.

2.3. Analytical method

Ash-sample AFT measurements were conducted on the ALHR-2 AFT analyzer under a reducing atmosphere (1:1, H_2/CO_2, volume ratio) based on Chinese Standard GB/T 219-2008. The ash was formed into a specific triangular ash cone, and was heated at 15 °C/min below 900 °C and at 5 °C/min thereafter. Four characteristic temperatures (deformation temperature (DT), softening temperature (ST), hemisphere temperature (HT), and FT) were recorded on the basis of a shape variation in the ash cone. The reported temperatures are the mean values of three duplicate experiments, and the standard deviations for the AFT (DT, ST, HT, FT) measurements were all below 5 °C.

Table 3
Ash compositions of samples.

Samples	Ash composition										
	A/B	SiO_2	Al_2O_3	K_2O	MgO	CaO	Fe_2O_3	SO_3	Na_2O	P_2O_5	TiO_2
NT	8.05	46.72	37.29	0.47	1.26	3.93	4.26	3.28	0.73	0.12	1.72
PZ	4.78	44.05	34.39	1.09	1.91	5.87	6.91	2.77	0.87	0.89	1.19
BD	4.56	43.84	32.16	0.76	1.73	8.62	5.18	4.37	0.82	0.46	2.06
XY	0.84	31.06	13.32	2.08	2.88	24.61	23.96	0.99	0.20	0.16	0.74