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Ash deposition characteristics of Moolarben coal and its blends during coal combustion

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Abstract−We report a systematic and comprehensive laboratory investigation of the ash deposition behavior of Moolarben (MO) coal, which has recently begun to be imported into Korea. Ash deposition experiments were conducted in a drop tube reactor, and a water-cooled ash deposit probe was inserted into the reactor to affix the ash. The tests were conducted using five types of single coals (two bituminous and three sub-bituminous, including MO coal) and blended coals (bituminous coal blended with sub-bituminous coal). Two indices represent ash deposition behavior: capture efficiency and energy-based growth rate. A thermomechanical analysis evaluated the melting behavior of the resulting ash deposits. The MO coal had the least ash deposition of the single coals due to its high melting temperature, indicated by high ash silica content. Indonesian sub-bituminous coals formed larger ash deposits and were sticky at low temperatures due to relatively high alkali content. However, blends with MO coal had greater ash deposition than blends with other bituminous coals. This non-additive behavior of MO coal blends is likely due to interactions between ash particles. Coals with higher silica content more effectively retain alkali species, resulting in lower melting temperatures and larger ash deposits. Therefore, we recommend that when blending in a boiler, silica-rich coals (SiO_2>80%, SiO_2/Al_2O_3>5) should be blended with relatively low-alkali coals (Na_2O+K_2O<3%), and the blending ratio of the silica-rich coals indicates less than 10%, which can safely operate the boiler.

Keywords: Moolarben Coal, Ash Deposition, Capture Efficiency, Blended Coal

INTRODUCTION

Mineral matter in coal causes fouling and slagging in boilers during coal combustion. Coal mineral matter is one of the most important factors affecting beneficiation, influencing furnace operations and boiler management procedures [1,2]. To date, experimental indices based on coal composition have been used to predict ash deposition and slagging/fouling potential [3]. Deposition characteristics can also be predicted through simple mechanical approaches [4,5]. However, it is difficult to determine the behavior of inorganic matter in an operational system based on results acquired from fixed bed instruments [6,7]. Thus, the non-additive depositional effects of various coal blends have been investigated using drop-tube reactors (DTR), which provide a reasonable compromise between test and actual conditions while maintaining flexible control of experimental conditions. Rushdi et al. [8] and Barroso et al. [9] used an entrained flow reactor to characterize the non-additive deposition behavior of several coals/blends under different experimental conditions. While many studies have been conducted to better understand ash deposition and the behavior of inorganic matter within boilers, further research is still needed.

Moolarben coal is imported at a rate of 500,000 t/yr and used in five coal-fired power plants in Korea. When Moolarben coal is blended with low-quality coals and used in boilers, significant slagging is observed in the super- and re-heaters, forming clinker that damages the boiler hoppers. Hence, detailed analysis of Moolarben coal and the ash deposition mechanisms that influence slagging propensity is needed. We investigated the ash deposition characteristics of Moolarben coal by measuring the qualitative capture efficiency (CE) and energy-based growth rate (GRE) of single coals and blends of Moolarben coal using a DTR equipped with an ash probe. A thermomechanical analysis (TMA) was used to analyze ash-melting behavior.

EXPERIMENTAL SECTION

1. Drop-tube Reactor and Deposit Probe

Fig. 1 presents a schematic of the DTR apparatus and deposit probe used in this study; the DTR (600.0 mm long with an internal diameter of 70.0 mm) was designed at the Pusan Clean Coal Center, Republic of Korea [10]. The experiments were designed to reproduce relevant parameters of operating systems, e.g., particle

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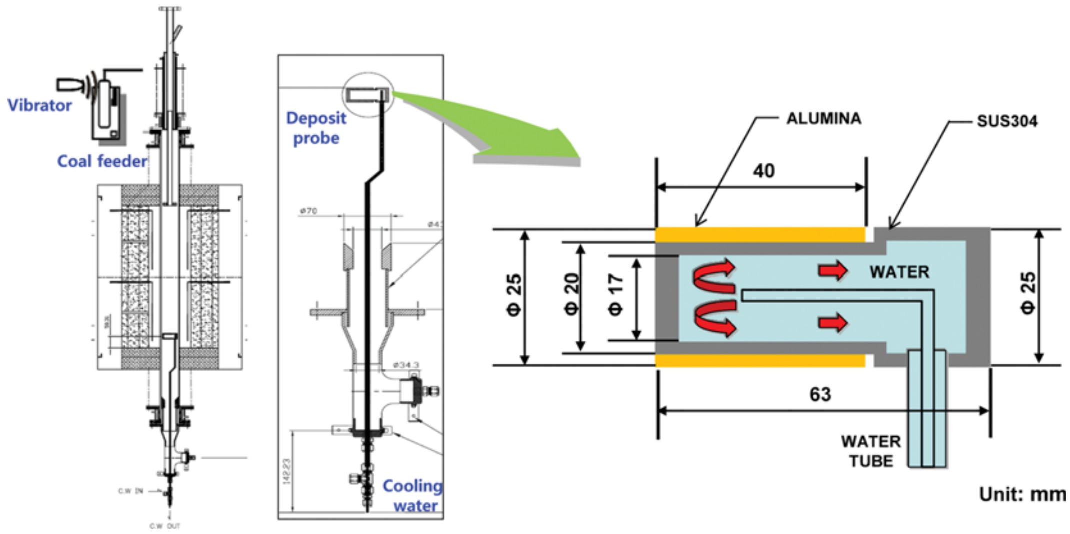

Fig. 1. Schematic of the drop tube reactor (DTR) apparatus and deposit probe.

Table 1. Properties of the coals used in this study

	Moolarben (MO)	Glencore (GL)	Bara-multi (BM)	Tanito (TA)	Berau (BE)
Origin	Australia	Russia	Indonesia	Indonesia	Indonesia
Heating value, MJ/kg					
HHV[a]	25.32	25.28	22.93	23.69	21.87
LHV[b]	24.21	24.11	21.66	22.44	20.52
Proximate analysis (% by weight, as received)					
M[c]	2.50	9.32	13.01	13.83	15.00
VM[d]	31.50	33.03	40.51	39.60	39.00
Ash	16.80	10.58	5.04	5.01	5.70
FC[e]	49.20	47.07	41.44	41.56	40.30
Ultimate analysis (% by weight, dry ash-free basis)					
C	83.76	62.31	75.27	73.93	74.64
H	5.26	4.96	5.83	4.91	5.22
O	8.00	29.50	16.76	18.15	17.32
N	2.36	2.63	2.01	1.75	1.64
S	0.63	0.61	0.14	1.26	1.18
Sum	100.00	100.00	100.00	100.00	100.00
Mineral composition (% by weight)					
SiO_2	82.4	58.12	48.00	43.52	43.52
Al_2O_3	15.2	23.60	18.60	26.43	26.43
Fe_2O_3	0.48	6.22	11.30	10.40	14.22
CaO	0.10	3.70	7.20	4.43	4.43
MgO	0.09	1.45	4.04	1.91	1.91
Na_2O	0.03	0.40	2.34	1.53	3.57
K_2O	0.37	1.96	1.40	1.72	1.23
SO_3	-	1.67	2.85	1.63	1.63
TiO_2	0.70	0.98	0.81	0.66	0.66
Others	0.63	1.90	3.46	7.77	2.4
IDT[f]	1833	1578	1403	1483	1413

[a]HHV: higher heating value [b]LHV: lower heating value [c]M: moisture
[d]VM: volatile matter [e]FC: fixed carbon [f]IDT: initial deformation temperature (K)

heating rates and gas temperature and composition, to study pulverized fuel (PF) combustion-related processes in detail. The DTR in this study was modified with an ash deposit probe to investigate the characteristics of coal ash deposition (Fig. 1). Ash deposits were collected on an alumina tube fitted at the end of the probe, inserted perpendicular to the flow direction inside the DTR. The alumina tube is a hollow cylinder (length 40 mm, outer diameter 25 mm) internally cooled by a water jacket. The probe is supported on a structure designed to allow the positioning of the tube at any location over the lower half length of the DTR to maintain a constant temperature. It is inserted through the outlet of the DTR and is used to characterize the particles impacting the ash deposition probe.

2. Test Conditions and Coals

The temperature inside the reactor was selected to produce slagging; 1,500 K was used for all experiments. The probe was located 10 cm upstream of the exit of the DTR, where particles have a relatively low carbon content (<1% unburned carbon). A total of 12 g of coal was injected at a feed rate of 0.2 g/min for 1 h. The coal particle size was 75-95 μm and the particle residence time was 2.21 s, assuming particle slip velocities based on Stoke's Law. The total gas flow rate with a mix of O_2 and N_2 was 8.3×10^{-5} m^3/s. For all experiments, the coal feeding and air transport rates were adjusted so that the excess oxygen coefficient was maintained at 1.16 (v/v dry), which is a typical furnace exit value for large PF boilers. The weights of the deposits were calculated based on the difference in weight between the clean and fouled samples and were used to derive indices for deposit growth rates. Proximate and ultimate analyses of the coals using standard American Society for Testing and Materials procedures are summarized in Table 1, including ash mineral matter and initial deposition temperature (IDT). Each bituminous coal was blended manually with three types of Indonesian coals before experiment. The blending ratio was one bituminous coal (30%) with one sub-bituminous coal (70%) by weight, typical of combinations used in Korean power plants.

3. Data Analysis

3-1. Capture Efficiency and Energy-based Growth Rate

Deposition was evaluated based on the weights of the deposits obtained in the DTR tests. The results were normalized to account for differences in coal feeding rates. CE and GRE were calculated using Eqs. (1) and (2), respectively, and the particle data obtained during the experiments. The CE (g deposit/g ash %) is the percentage of mineral mass captured, irrespective of the amount of ash contained in a particular coal, and represents the tendency of the particles to form a deposit. The GRE (g deposit/MJ) considers the amount of coal fed and its heating value to attain a certain thermal input, or the growth of the deposit per unit of thermal power produced from combustion [9,11].

$$\mathrm{CE}=\frac{m_{Dep}}{m_{Ash}\left(\frac{A_{coupon}}{A_{reactor}}\right)}\times 100 \tag{1}$$

$$\mathrm{GRE}=\frac{m_{Dep}}{\mathrm{LHV}\cdot m_{Fuel}} \tag{2}$$

where m_{Dep}, m_{Ash}, and m_{Fuel} denote the weight (g) of the deposit accumulated in the tube, the total fly ash flowing towards the tube in the reactor, and the coal fed during the test period, respectively. A_{coupon} and $A_{reactor}$ are the projected areas of the coupon and the cross-section of the DTR.

3-2. Particle Viscosity

Many models have been developed to predict particle viscosity (Pa·s) [12-14] and generally relate viscosity to temperature and coal composition based on empirical data fitting. The Urbain model [12] was considered best suited for predicting the viscosity of coal particles in this study and can be expressed as follows:

$$\mu_p=aT_p\exp\left(\frac{1000b}{T_p}\right) \tag{3}$$

where μ_p and T_p are the particle viscosity (Pa·s) and particle temperature (K), respectively; a (Pa·s/K) and b (K) are empirically derived, as follows:

$$\begin{aligned}
&a=\exp(-0.2693b-13.9751)\\
&b=b_0+b_1SiO_2+b_2SiO_2^2+b_3SiO_2^3\\
&b_0=13.8+39.9355\omega-44.049\omega^2\\
&b_1=30.481-117.1505\omega+129.9978\omega^2\\
&b_2=-40.9429+234.0486\omega-300.048\omega^2\\
&b_3=60.7619-153.927\omega+211.161\omega^2
\end{aligned} \tag{4}$$

$$\begin{aligned}
&\omega=\frac{x_m}{x_m+x_a}\\
&x_a=Al_2O_3+Fe_2O_3+B_2O_3\\
&x_m=FeO+CaO+MgO+Na_2O+K_2O+MnO+NiO\\
&\quad+2(TiO_2+ZrO_2)+3CaF_2
\end{aligned}$$

where x_a and x_m are the sums of the mole fractions of amphoterics and glass modifiers, respectively (grouped according to oxygen content).

3-3. Empirical Indices for Predicting Ash Deposition

A number of empirical indices are commonly used to predict

Table 2. Formulas for indices predicting ash deposition

Index	Formula
B/A[a]	$\frac{Fe_2O_3+CaO+MgO+Na_2O+K_2O}{SiO_2+Al_2O_3+TiO_2}$ where, $Fe_2O_3+CaO+MgO+Na_2O+K_2O+SiO_2+Al_2O_3+TiO_2=100\%$
Rs[b]	$\frac{B}{A}\times S$ where, S is the sulfur percent on a dry basis
Si_R[c]	$\frac{SiO_2}{SiO_2+Fe_2O_3+CaO+MgO}$
Rvs[d]	$\frac{(T^{e}_{250}-T^{g}_{10,000})}{54.17\times F_s}$ where, $F_s=10^{(0.00186\times T^{f}_{2,000}-1.933)}$

[a]B/A: base/acid ratio [15]
[b]Rs: slagging factor with sulfur contents [16]
[c]Si_R: silica ratio [17]
[d]Rvs: viscosity slagging index [19,20]
[e]T_{250}, [f]$T_{2,000}$, [g]$T_{10,000}$: particle temperature (K) corresponding to a viscosity of 250 Pa·s, 2,000 Pa·s, 10,000 Pa·s

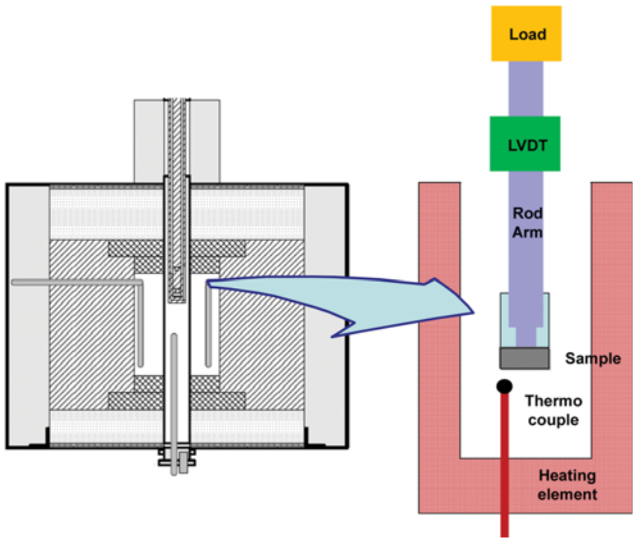

Fig. 2. Schematic of the thermomechanical analysis (TMA) apparatus.

the ash deposition behavior of coals based on their chemical properties, e.g., Winegartner [3] and Bott [4]. Some of these indices were selected for comparison with our experimental results; their definitions are provided in Table 2.

3-4. Thermomechanical Analysis

Thermomechanical analysis (TMA) was used to study the thermal behavior of ash from the coals and blends, to compare the ashes in terms of their potential to form deposits, and to assess the characteristics of the deposits. Fig. 2 shows a schematic of the TMA apparatus. The TMA procedure involved heating 200 mg of ash from 1,100 to 1,900 K at 5 K/min under a 60 g load. Penetration of a ram into the sample was subsequently measured [8]. Lab-ash produced from each of the coals and blends at 1,273 K over 1.5 h was used to find the TMA values, represented as penetration curves.

RESULTS AND DISCUSSION

1. Ash Deposition Characteristics for Single Coals

Using a digital camera, images were taken of the entire surface of the probe, showing the ash deposits for each single coal sample (Fig. 3). MO coal ash had a silica content of 82.4% and GL had the second-highest silica content of 58.12% (Table 1). The three Indonesian sub-bituminous coals (BM, BE, and TA) became sticky and congealed upon combustion (Fig. 3). Due to the low melting temperature of alkali matter contained in Indonesian coals, the slagging propensities of these coals are relatively high. To demonstrate this qualitatively, CE was compared among the coals (Fig. 4). CE was lowest for MO coal, followed by GL, BM, TA, and BE. BE had the most iron and sodium among the coals (Table 1). The sticky parts of the deposits congealed due to the low melting temperature, resulting in increased deposition on the probe (Fig. 3) [15]. These results are consistent with the normalized empirical indices of previous studies (Table 2; Fig. 4).

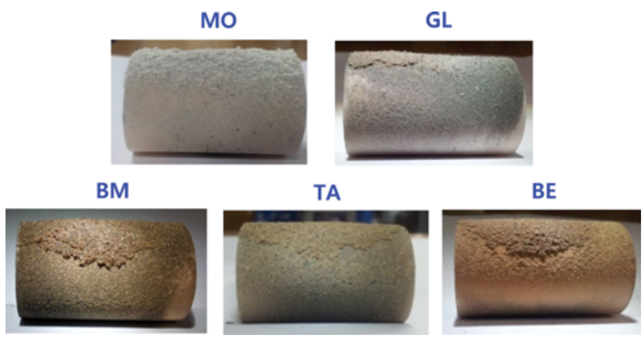

Fig. 3. Images of ash deposits on the probe for single coal samples.

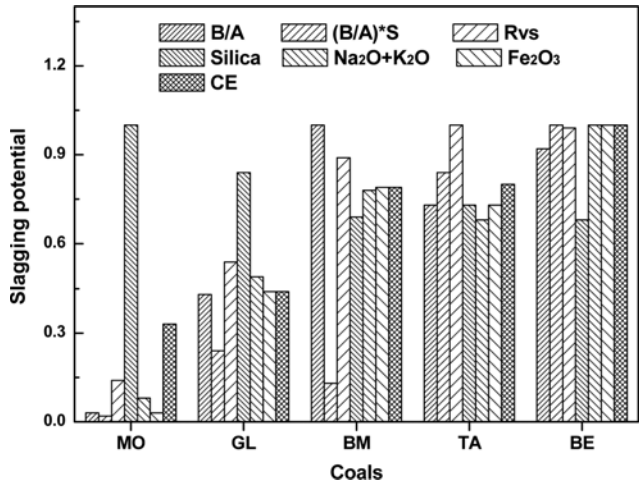

Fig. 4. Comparison of normalized slagging propensity with existing indices and CE for each coal type.

The basic to acidic oxide ratio (B/A ratio) of the coals also assists in distinguishing their deposition characteristics. Generally, an increase in the B/A ratio of the coal results in a lower melting temperature [15,16]. In decreasing order, the computed B/A ratios suggested that the slagging potential of the sub-bituminous coals (BE, TA, and BM) was greater than that of the GL and MO coals (Fig. 4). Another important parameter in determining the slagging potential of coal is its iron oxide content. High iron content generally lowers slag viscosity [17], which results in high ash deposition. BE coal had the highest Fe_2O_3 content, followed by BM, TA, GL, and MO (Fig. 4). Therefore, their slagging propensities would be expected to fall in this same descending order. Slagging propensity is also proportional to the alkali content (Na_2O+K_2O) of the coal with a similar effect to iron oxide [18], as all these compounds have high reactivity and form silicates with low melting points.

The Rvs index is used to predict slagging propensity based on the viscosity and temperature of the coal ash. High silica in the ash results in greater covalence, which yields a high-viscosity liquid phase and low deposition (Fig. 5) [19]. At high temperatures, when the viscosity is independent of the shear rate, slag flow is more efficient [20]. We used an Rvs index based on the temperatures at which the viscosities were 250 and 10,000 Pa·s, as well as the average temperature corresponding to a viscosity of 2,000 Pa·s. Viscosity was predicted using the Urbain model in Eq. (3), the results of which were applied to determine the Rvs index. MO coal was predicted

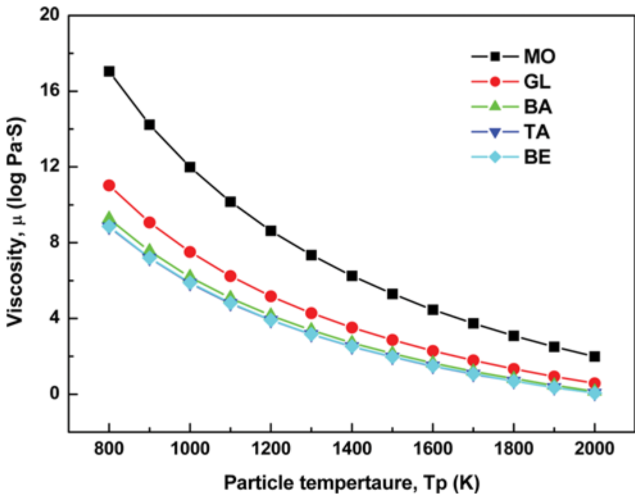

Fig. 5. Predicted viscosity characteristics for each coal type as a function of temperature.

to have the highest viscosity, followed by GL, BM, TA, and BE (Fig. 5). Guided by the viscosity index, MO and GL coals were expected to have less deposition, while BE, TA, and BM were expected to have more deposition. This hypothesis is consistent with the ash melting temperature and IDT of the coals (Table 1). MO and GL coals had higher melting temperatures and BE, TA, and BM coals had lower melting temperatures, consistent with application of the existing indices.

Thus, the chemical compositions of the ashes are important, as they strongly influence ash-melting temperatures, which in turn affect slagging propensity. The slagging indices based on chemical composition were able to predict slagging potential for single coals, confirmed by the CE. Therefore, there is no evidence for non-additive phenomena in single coals.

2. Ash Deposition Characteristics of Blended Coals

Fig. 6 shows images of the ash deposits on the probe for the blended coals. The blends comprised 30% bituminous coal (MO or GL) and 70% sub-bituminous coal (BE, BM, or TA). Ash fouling the coupon was collected and the amount normalized to determine the CE and GRE (Fig. 7). Quantitative values for MO and GL coals blended with the three Indonesian coals were compared with those of single coals.

The CE of MO alone was lower than that of GL. However, MO

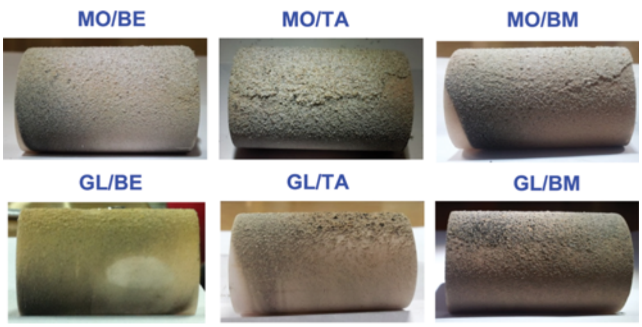

Fig. 6. Images of ash deposits on the probe for blended coals.

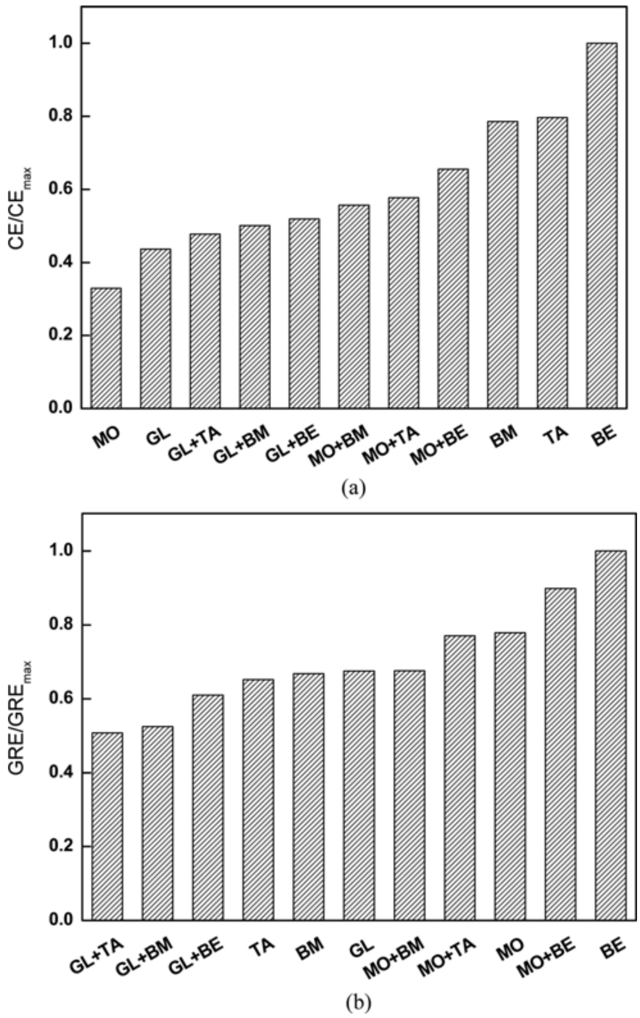

Fig. 7. Normalized capture efficiencies (CE) (a) and energy-based growth rates (GRE) (b) for single and blended coals, ordered from lowest to highest CE and GRE.

blends had higher CE values and larger deposits than GL blends (Fig. 7(a)). This behavior provides strong evidence for non-additive behavior due to blending and indicates that the relative performance of the blended coals is not the same as that of the parent coals.

Holger et al. [21] suggested that release of alkali species during coal combustion results in formation of large amounts of silica-rich deposits. Similarly, Hao et al. [22] reported that the higher molar ratio of $SiO_2:Al_2O_3$ in the coal resembled that of kaolinite ($Al_2O_3\cdot 2SiO_2$), a mineral with a high capacity for capturing gaseous alkali species. Aluminosilicates such as kaolinite react with alkali species as follows: $M^+ + Al_2O_3\cdot xSiO_2 \rightarrow M\cdot Al_2O_3\cdot xSiO_2$ (M=Na, K). Thus, alkali species are incorporated into the aluminosilicate structure, resulting in formation of albite or nepheline at high temperatures [21]. In the present study, the $SiO_2+Al_2O_3$ content of the MO coal deposit was 97.6% and that of GL was 81.7%. In addition, the $SiO_2:Al_2O_3$ ratio of MO was 5.4 and that of GL was 2.4, indicating that MO blends would likely form larger deposits than GL blends due to formation of a larger amount of aluminosilicates. Therefore, the

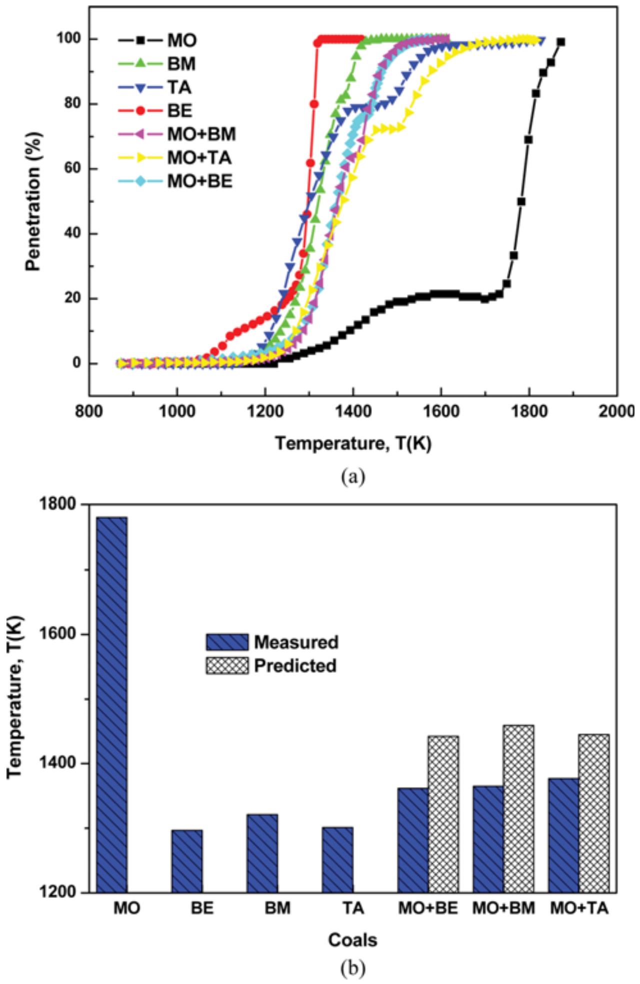

Fig. 8. Penetration curves (a) and temperatures at 50% penetration (b) for single coals and blends.

CEs for MO blends were higher than for GL blends. These results were clearly confirmed by the GREs (Fig. 7(b)). The GREs for MO blends suggested a much higher slagging potential than those for GL blends. These results indicate that MO blends may cause serious problems under practical operating conditions.

TMA tests were conducted to confirm the ash deposition behavior of MO and its blends observed in the DTR experiments. This test shows the potential for coals and blends to form ash deposits by characterizing their melting behavior, which is related to the chemical composition of the coal and interactions between the coals in the blend. The resulting penetration curves show that MO had the lowest ash melting temperature (Fig. 8(a)), consistent with the slagging indices and DTR deposition experiments. For example, temperatures at 50% penetration for MO, BE, BM, and TA were 1,781, 1,297, 1,321, and 1,301 K, respectively. However, MO blends with Indonesian coals showed very interesting results. Fig. 8(b) shows the temperatures at 50% penetration in the TMA tests for MO and its blends compared to the theoretical values calculated for the blending ratios. The measured temperatures at 50% penetration for MO+BE, MO+BM, and MO+TA were as low as 80, 94, and 68 K. Therefore, the ash particles of MO coal blended with Indonesian coals

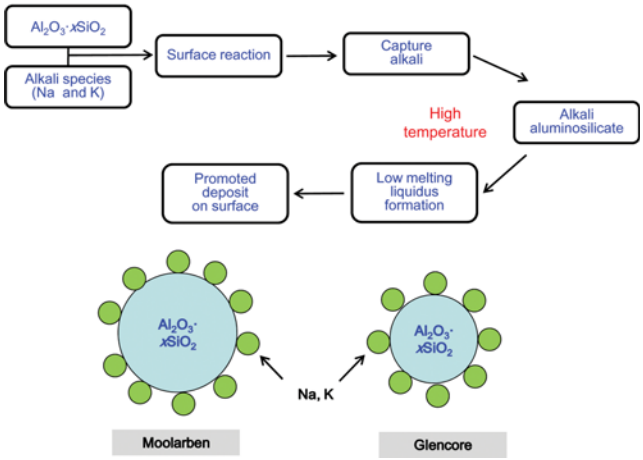

Fig. 9. Mechanism of ash deposition for Moolarben coal.

melted at much lower temperatures than the single coals [23].

The ash deposition mechanism of MO blends is shown in Fig. 9. MO has a significantly higher silica content than the other coals, resulting in the lowest slagging propensity. However, when it is blended with Indonesian coals, which have high alkali contents, the ash deposition results are contrary to what is expected. The alkali materials in the coal are released as vapors at high temperatures and captured by kaolinite, producing alkali aluminosilicates such as Na-Al-Si and K-Al-Si through surface reactions between kaolinite and the alkali species during combustion. These alkali aluminosilicates produce low melting point liquids, enhancing mineral melting and coalescence. Therefore, when the alkali aluminosilicates impact the surface of the tube, ash deposition is promoted due to their low melting temperatures. This mechanism is supported by the results of the TMA and DTR experiments and provides useful insights for blending processes in power plants that import and use Indonesian coals. To reduce the damage caused by slagging and fouling when silica-rich coals are used in blended fuels for boilers, coals that have relatively low amounts of alkali species should be used in the blends. The blending ratio of silica-rich coals should be carefully controlled and, practically, it should be blended less than 10%, which has little impact on slagging/fouling and can safely operate in a boiler. More detailed studies are needed for effective use of silica-rich coals, including determination of optimal blending ratios, blending sizes, etc.

CONCLUSIONS

We investigated the ash deposition behavior of MO coal and its blends. The primary conclusions were as follows:

- For single coals, MO is rich in silica and has the least ash deposition due to its high melting temperature. However, the subbituminous coals from Indonesia have high alkali contents and become sticky at low temperatures. Thus, the mineral compositions of the ash influence the melting temperature. The slagging propensities of the single coals are consistent with the predictions of empirical indices.
- For blended coals, the ash deposition of MO blended with Indo-

nesian coals is greater than that of GL blends, in contrast to the trends for single coals. The higher silica content of the MO coal increases capture of alkali species, resulting in a lower ash melting temperatures and promoting ash deposits. These results suggest that when a silica-rich coal (SiO_2>80%, SiO_2/Al_2O_3>5) is blended in a boiler, adding a coal that has relatively low alkali content (Na_2O+ K_2O<3%) is recommended. Blending ratios of silica-rich coals with high-alkali coals should be blended less than 10%, which has little impact on slagging/fouling and can safely operate in a boiler.

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