AFRC 2010 Pacific Rim Combustion Symposium, Maui, Hawaii, Sep.26-29, 2010

Ash Deposition Behavior of Upgraded Brown Coal in Pulverized Coal Combustion Boiler

Katsuya Akiyama[a], Haeyang Pak[a], Yoji Takubo[a], Toshiya Tada[b],
Yasuaki Ueki[c], Ryo Yoshiie[d], Ichiro Naruse[d]

[a] Mechanical Engineering Research Laboratory, KOBE STEEL, LTD., 1-5-5 Takatsukadai, Nishi-ku, Kobe, 651-2271, JAPAN
[b] Coal and Energy Technology Department, KOBE STEEL, LTD., 2-3-1 Niihama, Arai-cho, Takasago, 676-8670, JAPAN
[c] Energy Science Division, EcoTopia Science Institute, NAGOYA UNIVERSITY, Furo-cho, Chikusa-ku, Nagoya, 464-8603, JAPAN
[d] Department of Mechanical Science & Engineering, NAGOYA UNIVERSITY, Furo-cho, Chikusa-ku, Nagoya, 464-8603, JAPAN

Correspondence author: Katsuya Akiyama
E-mail: akiyama.katsuya@kobelco.com

Abstract

Ash with a low melting point causes slagging and fouling problems in pulverized coal combustion boilers. Ash deposition on heat exchanger tubes reduces an overall heat transfer coefficient due to its low thermal conductivity. Purpose of this study is to evaluate the ash deposition for Upgraded Brown Coal (UBC) and bituminous coal in a 145 MW practical coal combustion boiler. Melting temperature of the UBC ash is relatively lower than that of the bituminous coal ashes. Combustion tests are conducted, using the blended coal of 20 wt% of the UBC and 80 wt% of the bituminous coal. Before actual ash deposition tests, the molten slag fractions in those coal ashes were estimated by means of chemical equilibrium calculations. As the calculation results obtained, the molten slag fraction for the UBC ash reached approximately 90 % at 1523 K. However, that for the blended coal ash decreased until 50 %. These calculation results meant that blending of the UBC with the bituminous coal played a role in decreasing the molten slag fraction. The reason for this phenomenon was caused by formation of alumino-silicates compounds as a solid phase due to the coal blending. Next, the ash deposition tests were conducted, using a practical pulverized coal combustion boiler. A water-cooled stainless-steel tube was inserted at the locations at both 1523 K and 1273 K in the boiler to measure amount of the ash deposits. As a result, mass of the ash deposition for the blended coal did not greatly increase, compared with that for the bituminous coal alone. Therefore, the proper blending of the UBC with the bituminous coal enabled use of the UBC without the ash deposition problems in the practical boilers.

Key Words: Slagging, Fouling, Upgraded brown coal (UBC), Pulverized coal combustion boiler

1. Introduction

Bituminous coals, which are categorized as high-rank coals, are most commonly consumed in industrial sectors. In contrast, demand for low-rank coals such as sub-bituminous coal, lignite and brown coal is limited because of its lower calorific value and/or higher moisture content. Therefore, the low-rank coal is usually utilized as fuels only in some specific local regions around its mines. Recently, efficient technologies to utilize the low-rank coals have been focused due to limitation of the reserves of high-rank coals.

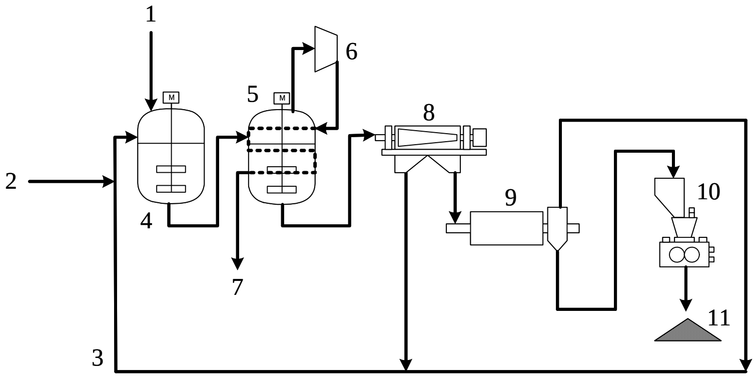
Some Indonesian low-rank coals have a feature of high moisture content, so that their heating values are relatively lower. However, contents of ash, nitrogen and sulfur in those coals are smaller. If effective drying or dewatering technologies for those coals could be developed, therefore, it would be possible to use them as new fossil fuels. Kobe Steel Co., Ltd. has developed an UBC process based on a slurry dewatering technology [1-3]. Akiyama *et al.* [4] also evaluated combustion characteristics of the UBC. However, ash melting points of the Indonesian low-rank coals are relatively lower. Therefore, slagging and fouling problems may occur in pulverized coal combustion boilers. Ash deposits on heat exchanger tubes reduce the overall heat transfer coefficient because of its low thermal conductivity. Consequently, it is difficult to use such the low-rank coals alone in the pulverized coal combustion boilers.

The ash deposition phenomena are influenced by coal type (ash compositions, melting temperature and distribution of mineral matter), reaction atmosphere, particle temperature, surface temperature of heat exchanger tubes, tube materials, flow dynamics and so forth. Several reviews relating to the ash deposition characteristics have already been reported [5]. For instance, Raask [6] elucidated the deposit initiation. Walsh *et al.* [7] and Baxter [8] studied the deposition characteristics and growth. Beer *et al.* [9] attempted to develop theories of the ash behavior. Benson *et al.* [10] summarized behavior of the ash formation and deposition during coal combustion. Li *et al.* [11] investigated coal char-slag transition under oxidation conditions. Naruse *et al.* [12] evaluated the ash deposition characteristics under high-temperature conditions. Bai *et al.* [13] studied characterization of low-temperature coal ash at high temperatures in a reducing atmosphere. Vuthaluru *et al.* [14] evaluated ash formation of brown coals. Abbott *et al.* [15] predicted ash behaviors using chemical equilibrium calculations. Hansen *et al.* [16] quantified ash fusibility using differential scanning calorimetry. Additionally, Gupta *et al.* [17] developed a mechanistic model for growth of the ash deposition during PF combustion. Hurley *et al.* [18] investigated the ash deposition at low temperatures in boilers burning high-calcium coals. Even for those references, however, precise and quantitative knowledge of the deposition of coal ash with a low-melting temperature in practical coal combustion boilers has been insufficient. Our previous studies [19] have proven that the molten slag fraction in ash obtained by chemical equilibrium calculations is one of the useful indices to predict the coal blending method to reduce the ash deposition.

The objectives of this study are to evaluate the ash deposition behavior such as slagging and fouling for an Upgraded Brown Coal (UBC) and a bituminous coal in a 145 MW practical coal combustion boiler. Melting temperature of the UBC ash is relatively lower than that of the bituminous coal ash. The combustion tests are conducted, using the blended coal of 20 wt% of the UBC with 80 wt% of the bituminous coal. Before actual ash deposition tests, the molten slag fraction in the coal ashes was estimated by means of chemical equilibrium calculations. Next, the ash deposition tests were conducted using the practical boiler during 8 days operation.

2. UBC Process

Figure 1 shows a schematic diagram of the UBC process. The UBC process developed by Kobe Steel Co., Ltd. can increase quality of the low-rank coal by means of a slurry dewatering technique at low temperature and pressure without chemical reactions. Our company started developing the UBC process for Australian brown coals in 1993. A 3 t/d pilot plant for an Indonesian low-rank coal has been operated successfully since 2001. Recently, a 600 t/d demonstration plant has been operated in Satui, South Kalimantan. In the UBC process, the low-rank coal is first crushed, and then is mixed with oil and a small amount of asphalt to produce the slurry. This coal–oil slurry is heated to be dewatered. The UBC produced adsorbs very little moisture since the asphalt can deactivate active sites on the dewatered coal effectively. After the coal is separated from the oil, it is dried and pressed to make transportable briquettes. As mentioned above, the UBC process can effectively remove the moisture in low-rank coals and can increase its heating value without changing its other properties. Therefore, the UBC produced from Indonesian low-rank coals has useful properties such as low nitrogen, sulfur and ash contents. However, this process cannot change melting point of the UBC ash any more.



1. Raw Coal
2. Additive (Asphalt)
3. Recycle Oil
4. Slurry Making Unit
5. Slurry Dewatering Unit (Evaporator)
6. Steam Compressor
7. Waste Water
8. Centrifugal Machine
9. Dryer
10. Roll Type Briquette Machine
11. UBC Briquette

Figure 1. Schematic diagram of UBC process.

3. Chemical Equilibrium Calculations

An Indonesian UBC and an Australian bituminous coal of Coal A were selected as samples. Those coal properties are shown in Table 1. As seen from the table, the hemispherical temperature for Coal A under the oxidizing condition is 230 K higher than that of the UBC. Prominent features of Coal A are higher SiO_2 content and lower CaO and Fe_2O_3 contents in the ash than that of the UBC. The ash particles tend to adhere more on the tube as an amount of the molten particles increases [19]. Therefore, the molten fractions of each ash were calculated by a chemical equilibrium theory, using Fact Sage Ver. 6.1 software. Table 2 shows conditions of the chemical equilibrium calculations. The gaseous compositions near a burner in the pulverized coal combustion boiler were given. In the calculations, the partial pressures of CO, CO_2 and H_2 gas were fixed. The calculations were carried out in 50 K increments to determine mass percentage of the molten slag in the ash in the temperature range of 1273–2073 K.

4. Experimental Section

Figure 2 shows a flow diagram of the coal combustion power station applied in this study. This power station is located in Kakogawa works of Kobe steel Co., Ltd., which was designed for bituminous coal combustion. The coal was fed into the coal mill, and was pulverized. The particle diameter was less than 75 μm, whose mass fraction was more than 85 wt%. Flue gas passed through the de-NO_x tower, air heater, electric precipitator and the de-SO_x tower. The ash deposition tests were carried out at the 145 MW boiler. Figure 3 shows a schematic diagram of the boiler and location of the ash deposition tests. It is a tangential firing boiler, which equipped 16 pulverized coal burners arranged in four rows on the walls in the furnace. The combustion air is separated into a primary air and an over-fire air (OFA). The ash deposits were collected from two different locations in the boiler of (A) the furnace wall beside the top burner at 1523 K and (B) the furnace wall beside the super heater at 1273 K.

Table 1. Properties of coals tested.

Coal sample			Coal A	UBC
Heating value [MJ/kg]			29.70	24.22
Proximate analysis [wt%, dry]	Ash		11.50	4.60
	Volatile matter		35.60	48.70
	Fixed carbon		51.54	45.98
Fuel ratio [-]			1.45	0.94
Ultimate analysis [wt%, daf]	Carbon		83.43	72.77
	Hydrogen		5.78	5.70
	Nitrogen		1.86	1.08
	Sulfur		0.73	0.11
	Oxygen (Balance)		8.20	20.34
Ash fusion temperature [K]	Oxyidizing	Initial deformation	1329	1426
		Hemisperical	1753	1523
		Fluid	>1823	1658
	Reducing	Initial deformation	1293	1340
		Hemisperical	1725	1503
		Fluid	1804	1610
Ash compositions [wt%]	SiO_2		60.80	40.70
	Al_2O_3		25.60	12.10
	CaO		2.79	11.90
	Fe_2O_3		4.83	16.00
	MgO		1.06	10.20
	Na_2O		0.23	0.11
	K_2O		0.95	0.83
	SO_3		1.80	7.80
	P_2O_5		0.22	0.05
	TiO_2		1.27	0.67
	V_2O_5		0.11	0.07
	MnO		0.04	0.37

Table 2. Conditions of chemical equilibrium calculations.

Temperature (K)		1273 ~ 2073
Gas composition (%)	O_2	8.3E-8
	CO_2	12.3
	CO	8.2
	H_2	1.5
	N_2	70.6
	H_2O	7.4
Ash composition (wt%)	SiO_2, Al_2O_3, CaO, Fe_2O_3, MgO, Na_2O, K_2O, SO_3 P_2O_5, TiO_2, V_2O_5, MnO	

The (A) and (B) correspond to slagging and fouling deposits, respectively. Table 3 shows the boiler operational conditions. Both Coal A and the blended coal of Coal A with UBC were burned in the combustion tests. The heat load was fixed at 145 MW for each test. The oxygen concentration in the flue gas was kept at 2.9 % as a wet basis. Ratio of the over-fired air to the total combustion air was 34.5 %. The ash deposition tube, which was made of stainless steel (SUS304), was inserted into the boiler to collect the slagging and fouling deposits as shown in Figures 4 and 5. The length and outer diameter of the ash deposition tube were 0.2 and 0.0318 m, respectively. The deposition probe mainly consisted of a test piece for deposition and a water-cooled probe. Two thermocouples were installed between the test piece and the water-cooled probe. The surface temperature of the test piece of deposition was assumed to be the

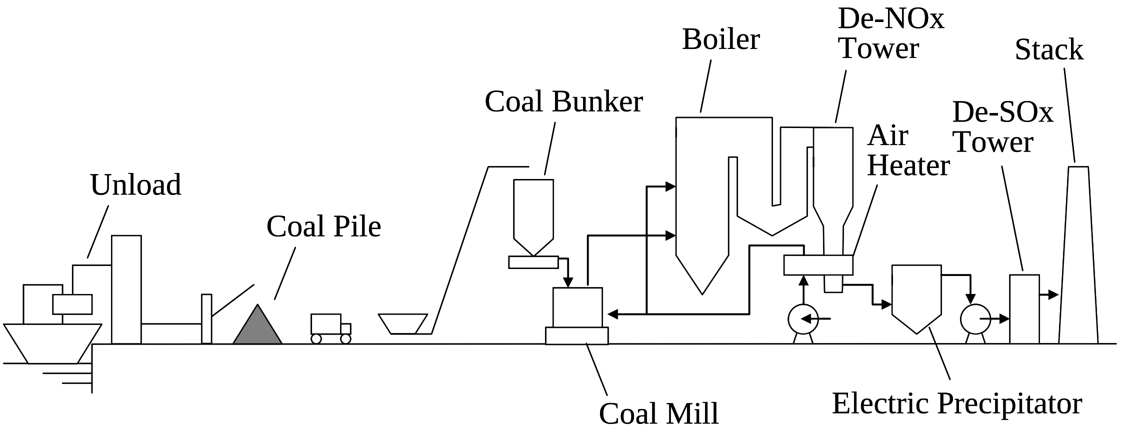


Figure 2. Flow diagram of coal combustion power station.

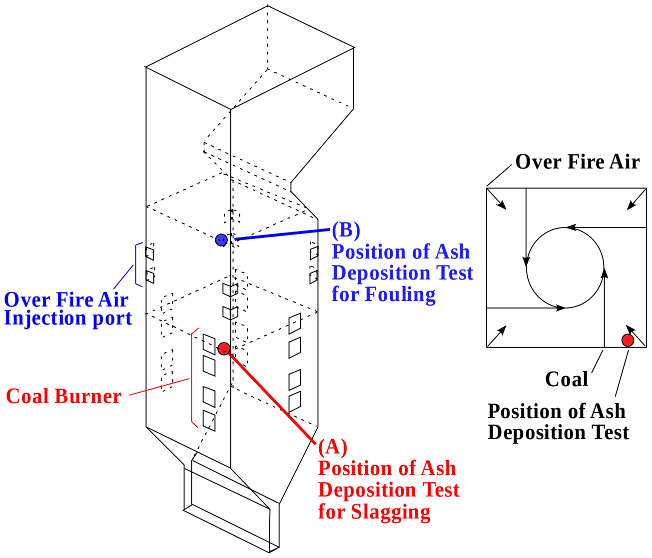


Figure 3. Schematic diagram of the boiler and location of the ash deposition tests.

Table 3. Operational conditions on boiler

Coal	Coal A, Coal A(80)+UBC(20)
Heat load [MW]	145
Quantity of evaporation [t/h]	450
Feed rate of coal [t/h]	55
Oxygeon concentration at boiler outlet [wet-%]	2.9
Combustion stoichiometric ratio at boiler outlet [-]	1.18
Ratio of over fire air to total combustion air [%]	34.5

temperatures measured by those thermocouples. The surface temperature was controlled at 723 K by adjusting flow rate of the cooling water inside the probe. The cross-sectional structures and compositions of ash particles on the tube were observed and analyzed, using a scanning electron microscopy (SEM) and an energy dispersive X-ray spectroscopy (EDX) apparatus, respectively.

Figure 4. Photo of the ash deposition test probe inserted in boiler.

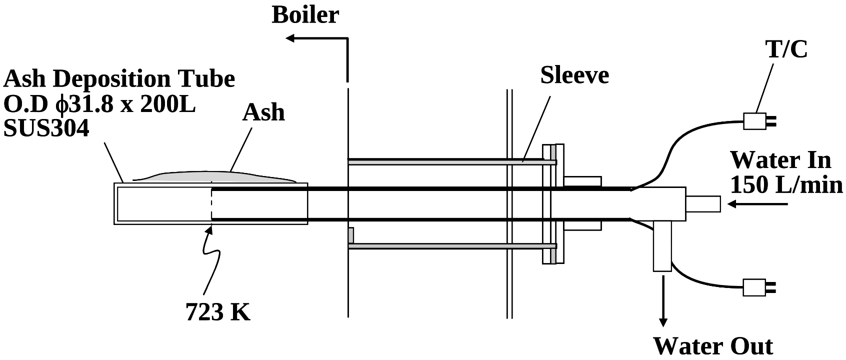


Figure 5. Schematic diagram of ash deposition test probe.

5. Results and discussion

5.1. Fraction of the molten slag obtained by chemical equilibrium calculation

Figure 6 shows calculated results of the molten slag fraction in ash for Coal A, UBC and the blended coal of them. The molten slag fraction is defined as the content of molten slag in the total ash. For the UBC ash, the molten slag forms at relatively low temperature, and the molten slag fraction rapidly increases between 1323 and 1573 K. For the Coal A ash, however, the molten slag does not form at temperature less than 1273 K, and the molten slag fraction gradually increases between 1273 and 1673 K. Additionally, when the mixing mass ratio of the UBC increases, the molten slag fraction in ash increases between 1323 and 1873 K.

Figure 7 shows relationship between the mixing fraction of UBC with Coal A and the molten slag fraction in ash at different temperatures. In this figure, the molten slag fraction of UBC ash reaches approximately 90 % at 1523 K. For the blended coal, however, it decreases to 50 %, which is close to the value of 43 % for Coal A. On the other hand, the molten slag from blended coal ash formed very little at 1273 K. The calculation results mean that this coal blending plays a role in reducing the molten slag fraction.

Figure 8 shows calculated results of the compositions in (a) the molten slag and (b) the solid phases for the UBC ash, Coal A ash and their blended coal ash at 1523 K. The minor components with less than 0.1 wt% in both the phases are negligible in this figure. For the UBC ash alone, SiO_2 slag is significant in the slag phase formed. When Coal A ash is mixed with the UBC ash, fraction of the molten slag phase deceases, and some alumino-silicates compounds are produced. As a result, a large amount of molten slag, including SiO_2, FeO and CaO decreased by mixing Coal A ash to the UBC ash.

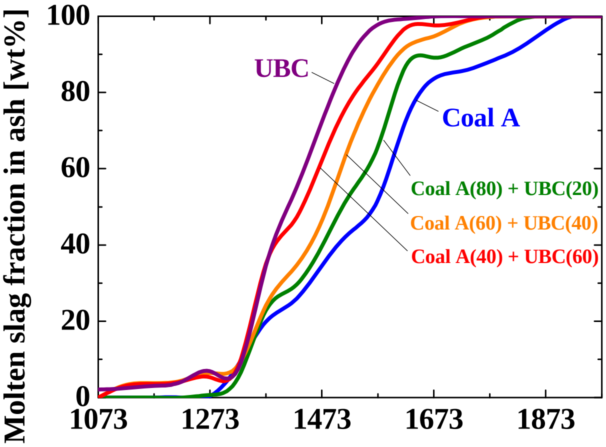


Figure 6. Calculated results of molten slag fraction in ash for blended coal of Coal A and UBC.

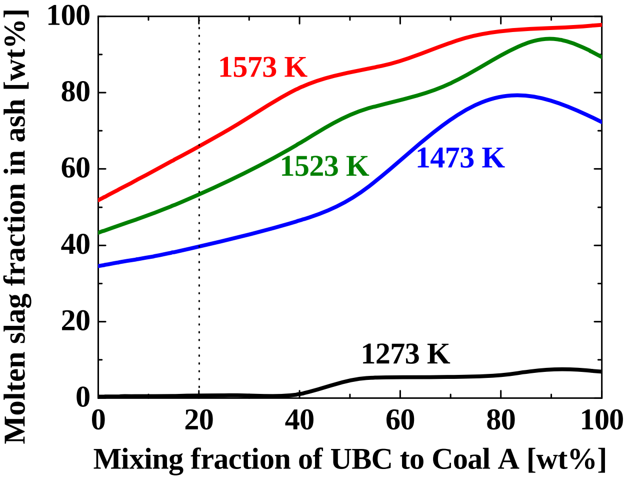


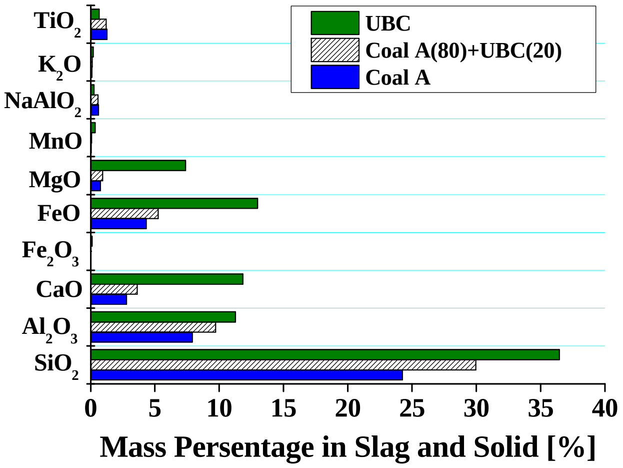
Figure 7. Relationship between mixing fraction of UBC with Coal A and molten slag fraction in ash with different temperatures.

5.2. Ash deposition behavior in the boiler

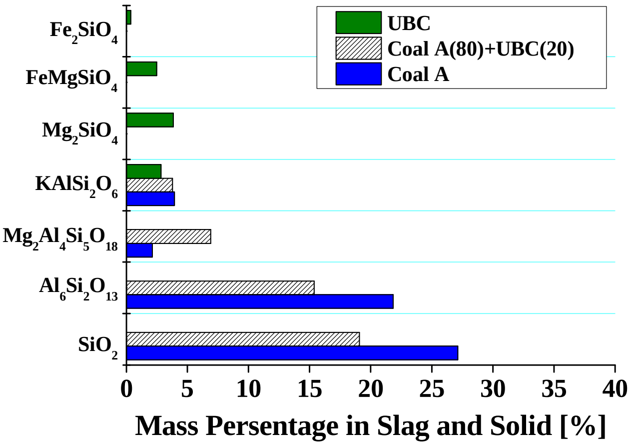
Figure 9 shows photos of the slagging and fouling areas at about 1523 K and 1273 K in the boiler, respectively. Circumstances of the ash deposition on the wall were observed, using a water-cooled CCD camera. The ash particles adhere around the burner for both Coal A and the blended coal. However, it did not grow to the large clinker. Additionally, it was observed that the ash adhered hard to the wall around the slagging and fouling areas in the boiler corners.

Photos of the ash deposition on the tube after 100 min of the exposure time are shown in Figure 10. For Coal A at 1523 K, numerous fine gray particulates seem to deposit on the surface, and some particulates agglomerate each other. For Coal A at 1273 K, numerous fine gray particulates without agglomeration seem to deposit on the surface. For the blended coal, color of the deposited ash turns to brown, but there is not large difference between Coal A and the blended coal.

Figure 11 shows results of mass of the deposited ash on the tube at 1523 K and 1273 K. The mass of deposited ash for the blended coal slightly increases, compared to that for Coal A. This is because that the molten slag fraction in ash for the blended coal at 1523 K increased and the surface of deposited ash became more sticky. However, the slagging and fouling problems did not occur during 8 days boiler operation. Therefore, this result suggests that the proper blending of UBC with bituminous coal enables the use of UBC without the ash deposition problems in the boiler.



(a) Compositions in the molten slag phase.



(b) Compositions in the solid phase.

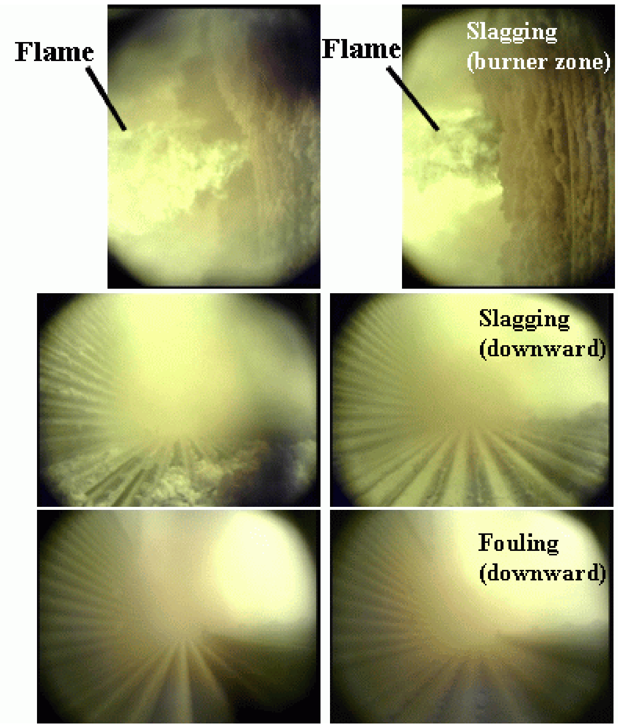
Figure 8. Calculated results of the compositions in the molten slag and solid phases for the UBC ash, Coal A ash, and their blended coal ash at 1523 K.

5.3. Mechanisms of the ash deposition in the boiler

Figure 12 shows the cross-sectional structures and compositions of the deposit on the tube at 1523 K. For the blended coal, the spherical particles exists more in the ash layer on the tube than for Coal A. This is because the molten slag fraction in ash for the blended coal at 1523 K is higher than that for Coal A. Even for the blended coal, however, sintering phenomenon does not occur in the ash deposition layer.

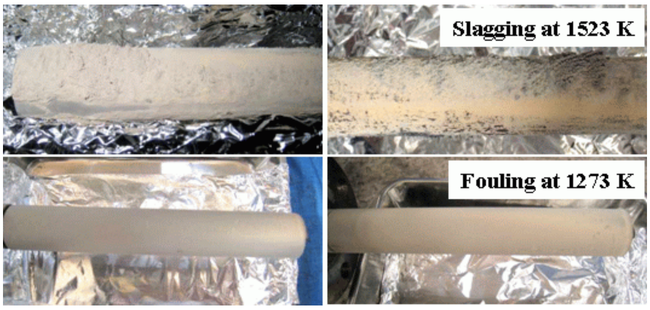
Figure 13 shows the cross-sectional structures and compositions of the deposit on the tube at 1273 K. The deposited ash for the blended coal consists of many spherical particles even though the temperature is lower. Particularly, the particles containing Mg is analyzed in the ash deposit with Si and Al elements. These Mg rich particles would be derived from the UBC ash, as shown in Table 1 and Figure 8.

Based on these observations, Figure 14 summarizes mechanisms of the ash deposition in the boiler. For the slagging behavior, the coal ash is partly fragmented and molten during combustion, and adheres to the tube surface. The blended coal ash particles react each other on the tube because residence time of the ash particles before adhering on the tube is short. According to the results of the chemical equilibrium calculations mentioned above, Coal A could reduce production of the molten slag in blending with the UBC. In other words, the surface state of the deposit would be dry, so that the UBC ash did not adhere to the tube strongly. For the fouling behavior, on the contrary, the ash in the original coal is influenced by the thermal history before adhering on the tube. If the melting point of the coal ash is low, the shape becomes spherical before adhering to the tube.



(a) Coal A (b) Coal A(80)+UBC(20)

Figure 9. Photos of slagging and fouling area in the boiler.



(a) Coal A (b) Coal A(80)+UBC(20)

Figure 10. Photos of ash deposition on the tube after 100 min.

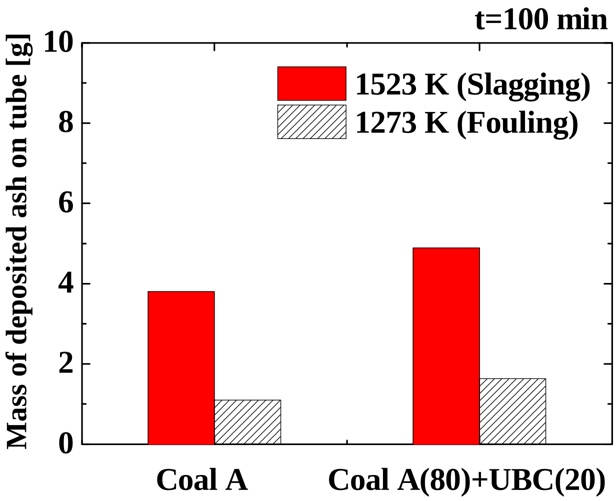
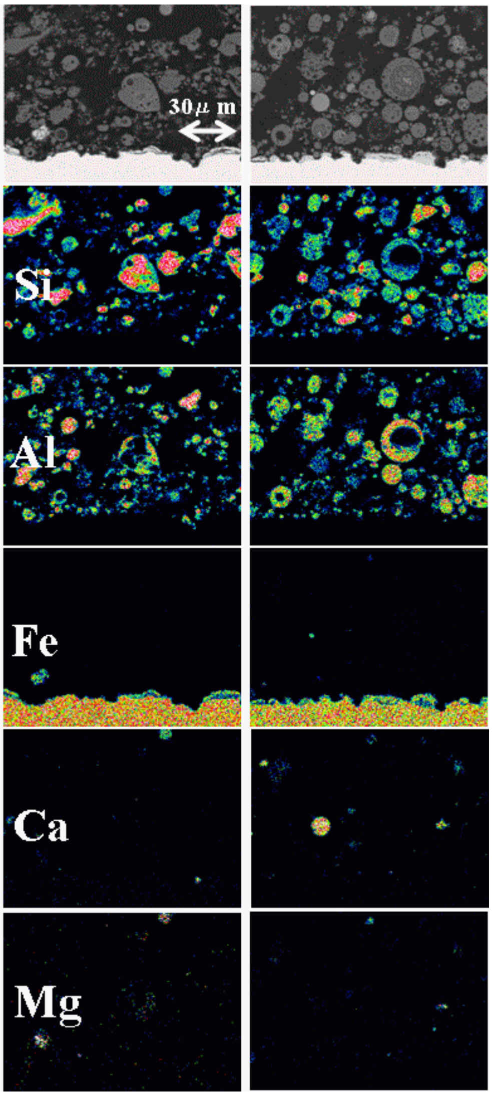
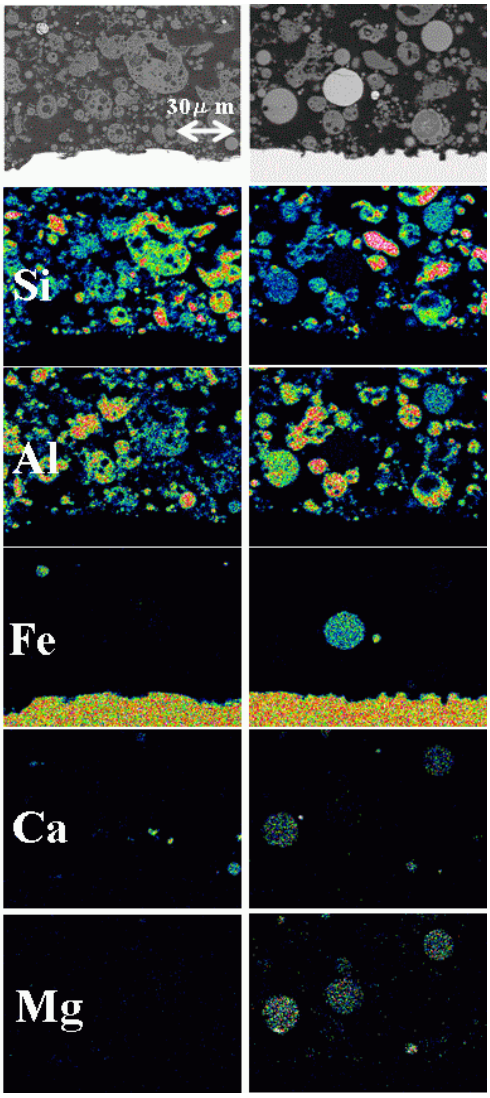


Figure 11. Results of mass of deposited ash on tube at 1523 K and 1273 K.



(a) Coal A (b) Coal A(80)+UBC(20)

Figure 12. Cross-sectional structures and compositions of the deposit on the tube at 1523 K.



(a) Coal A (b) Coal A(80)+UBC(20)

Figure 13. Cross-sectional structures compositions of the deposit on the tube at 1273 K.

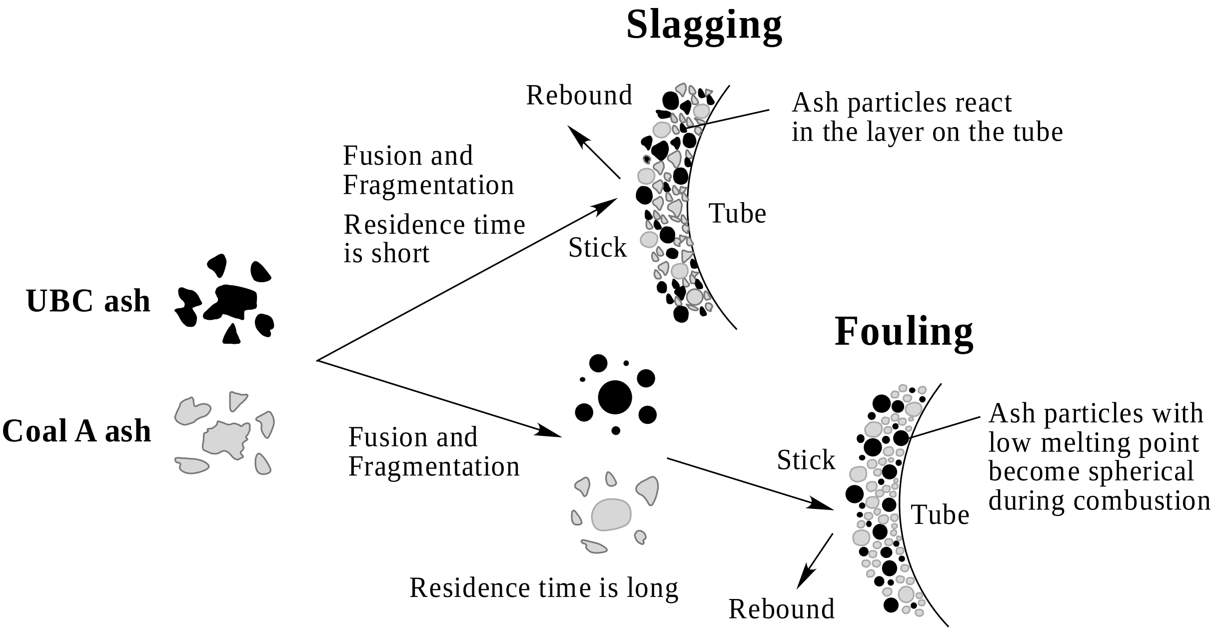


Figure 14. Mechanisms of the ash deposition in the boiler.

6. Conclusions

Chemical equilibrium calculations and the ash deposition tests were conducted in order to evaluate the ash deposition for Upgraded Brown Coal (UBC) and bituminous coal in a 145 MW practical coal combustion boiler. As a result, the bituminous coal blending with UBC played a role in reducing the molten slag fraction. This was because the solid phase compositions of alumino-silicates was produced due to the bituminous coal blending. Additionally, mass of the deposited ash for the blended coal did not greatly increased under the present blending condition. Therefore, the proper blending of UBC with bituminous coal enables the use of UBC with a low ash melting point without any ash deposition problems in the practical boiler.

Acknowledgments

This study was partly supported by JCOAL, which provided our UBC sample.

References

[1] Sugita S, Deguchi T, Shigehisa T, Katsushima S. Demonstration of UBC Process in Indonesia, ICCS&T, Okinawa, Japan, Oct. 2005.

[2] Sugita S, Deguchi T, Shigehisa, T. Demonstration of a UBC (Upgrading of Brown Coal) Process in Indonesia. Kobe Steel Eng. Rep. 2006; 56(2): 23-26.

[3] Yamamoto S, Sugita S, Mito Y, Deguchi T, Shigehisa T, Otaka Y. Development of Upgraded Brown Coal Process, The Institute for Briquetting and Agglomeration (IBA), Savannah, GA, Oct. 2007.

[4] Akiyama K, Tada T. Combustion characteristics of upgraded brown coal (UBC), Proc. 6th Int. Symp. Coal Combust., China, 2007, 527-532.

[5] Frandsen FJ. Ash Research from Palm Coast, Florida to Banff, Canada: Entry of Biomass in Modern Power Boilers. Energy Fuels 2009; 23(7): 3347-3378.

[6] Raask E. Mineral impurities in coal combustion, Hemisphere Publishing Corporation, Washington, 1985, 169-189.

[7] Walsh PM, Sayre AN, Loehden DO, Monroe LS, Beeŕ JM, Sarofim AF. Deposition of bituminous coal ash on an isolated heat exchanger tube: Effects of coal properties on deposit growth. Prog. Energy Combust. Sci. 1990; 16(4): 327-345.

[8] Baxter LL. Influence of ash deposit chemistry and structure on physical and transport properties. Fuel Process. Technol. 1998; 56 (1-2): 81-88.

[9] Beer JM, Sarofim AF, Barta LE. Inorganic transformations and ash deposition during combustion. In Engineering Foundation; Benson, S. A., Ed, ASME: New York; 1992.

[10] Benson SA, Jones ML, Harb JN. Ash formation and deposition Chap.4. In Fundamentals of coal combustion for Clean and Efficient Use, Smoot, L. D., Ed, Elsevier Science, New York, 1993, p. 299.

[11] Li S, Whitty K. J. Effect of Temperature and Residual Carbon. Energy Fuels 2009; 23(4): 1998-2005.

[12] Naruse I, Kamihashira D, Khairil, Miyauchi Y, Kato Y, Yamashita T, Tominaga H. Fundamental ash deposition characteristics in pulverized coal reaction under high temperature conditions. Fuel 2005; 84(4): 405-410.

[13] Bai J, Li W, Li B. Characterization of low-temperature coal ash behaviors at high temperatures under reducing atmosphere. Fuel 2008; 87(4-5): 583-591.

[14] Vuthaluru HB, Wall TF. Ash formation and deposition from a Victorian brown coal modelling and prevention. Fuel Process. Technol. 1998; 53(3): 215-233.

[15] Harb JN, Munson CL, Richards,GH. Use of equilibrium calculations to predict the behavior of coal ash in combustion systems. Energy Fuels 1993; 7(2): 208-214.

[16] Hansen LA, Frandsen, FJ, Dam-Johansen K. Ash fusion quantification by means of thermal analysis, An Engineering Foundation Conference on Impact of Mineral Impurities in Solid Fuel Combustion, Hawaii, Nov., 1997.

[17] Gupta S, Gupta R, Bryant G, Wall T, Watanabe S, Kiga T, Narukawa K. Characterization of Ash Deposition and Heat Transfer Behavior of Coals during Combustion in a Pilot-Scale Facility and Full-Scale Utility. Energy Fuels 2009; 23(5): 2570-2575.

[18] Hurley JP, Benson SA. Ash Deposition at Low Temperatures in Boilers Burning High-Calcium Coals 1. Problem Definition. Energy Fuels 1995; 9(5): 775-781.

[19] Akiyama K, Pak H, Tada T, Ueki Y, Yoshiie R, Naruse I. Ash Deposition Behavior of Upgraded Brown Coal and Bituminous Coal. Energy Fuels 2010; 24(8): 4138-4143.