INVESTIGATION OF ASH DEPOSIT FORMATION ON HEAT TRANSFER SURFACE OF BOILERS USING COALS AND BIOMASS

by

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Combustion of coals and biomass in boiler furnaces leads to formation of fireside deposits on irradiated and convective surfaces. This problem is not a new one, but it became one of the main operational problems in boilers using low rank coal and some sort of biomass. In the paper presented are the results of research of ash deposit processes in laboratory conditions. An experimental furnace was used for these purposes. The experiments were performed on a tubular experimental furnace which ensures appropriate temperature and mass transfer conditions for physical and chemical transformations of the mineral matter of fuel as in real conditions. The main working parameters can be varied in wide ranges. The influence of grinding fineness, excess air and wall surface temperature was analysed. Also, an ash related problems during coal and biomass combustion was considered. Key empirical correlations for slagging and fouling were tested. Two types of Serbian coals (Kolubara and Kosovo) and several biomasses were analysed. It was shown that many sorts of biomass and Kosovo coal have a great propensity to slagging and fouling.

Key words: *boiler, combustion, fouling, slagging, ash deposit, criterion, coal, biomass, laboratory furnace*

Introduction

Ash deposit on irradiated and convective heat transfer surfaces of boilers is one of the main operational problems at plants using low rank coals [1] or some type of biomass [2, 3]. The specific characteristics and composition of Serbian coals makes it impossible to directly use the results obtained from analysis of coals from basins in other countries. An extensive research program has been conducted with the main aim to investigate the processes of ash deposit formation and combustion of pulverized fuel (PF) in order to find criteria for estimating the tendency of particular fuel (coal and biomass) to form deposits and also to find aerodynamic, thermal and construction parameters which minimize the rate of deposit formation.

Experimental research of combustion and deposit formation processes under laboratory conditions can be carried out in small experimental furnaces, in which only partial modelling is possible and only the main similarity criteria are satisfied. Being aware of the complexity of combustion and ash deposit formation processes and of the fact that in principle it is not possible to obtain ideal similarity between the processes in a real large-scale furnace and ones in a small-scale model, a small experimental tubular furnace was built. During the construction of the experimental furnace the similarity of the following phenomena was satisfied: heat and mass

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transfer, combustion and physical and chemical transformations of the mineral matter in fuel [4].

In order to obtain similarity of the mentioned processes, the following conditions had to be satisfied: equality of the gas temperature and gas composition in the experimental and real furnaces, the same volume heat release, grinding fineness of the PF, relative gas velocity, residence time in experimental and real furnaces, temperature of the surface on which the ash deposit is formed.

Analysis of ash deposit formation process

Material and methods

By detailed analysis of the similarity conditions, the following dimensions and parameters were chosen for experimental furnace: diameter of the tubular furnace 71 mm, furnace height 2800 mm, gas temperature in furnace 1000-1200 °C, volume heat release 100-300 kW/m^3, excess air λ =1.2-1.5, gas velocity 4-5 m/s, fuel (Kolubara and Kosovo), fuel flow-rate 0.5-3 kg/h, and deposit probe surface temperature 450-550 °C [1, 4].

Experimental furnace can be divided into four functional parts: the tubular furnace itself, the PF preparation and feeding line, the air preparation and feeding line, and the flue gas line. The tubular furnace is made from a stainless steel tube. The flow of the PF-air mixture is upward. Along the furnace it is possible to take samples of particles and flue gases, or to take measurements of other parameters in the furnace, at four locations.

Four electric heaters placed around the furnace with power of 11.2 kW were used to raise and keep the furnace temperature at the desired level, to start the combustion process, and to create a homogeneous temperature field in the furnace. The furnace was insulated with several layers of mineral wool, vermiculite and ceramics. The PF preparation and feeding line includes a laboratory mill, standard screens and PF feeder. Primary and secondary air can be heated up to 400 °C by electric heaters and their flow rate can be measured by standard orifice. The mixture of prepared PF and primary air is injected into the furnace by a burner, and secondary air is injected concentrically around the burner. By using a ventilator, flue gases are exhausted into the atmosphere.

A special probe for ash deposits formation has been developed. It is possible to position this probe at four locations along the furnace. The construction of the probe provides the following: constant wall temperature t_w = 450-550 °C by cooling with air, easy handling and ash deposit removal, cooling of both ends of the probe, t_w and heat flux measurements at the place of ash deposit formation, and t_w regulation. By measurements of the thickness of the deposit and by further their analysis, it is possible to obtain the following data: rate of the deposit formation for different t_w, gas parameters, different fuels and grinding fineness, physical and chemical properties of the ash layer as the function of the same parameters, change of t_w as the function of the layer thickness and deposit characteristics.

Experimental results

The main experiments planned on the experimental furnace were the research of ash deposit formation processes and the rate of deposit formation. The nature of these processes in furnaces is different, which induces that deposits have different characteristics like mechanical strength, chemical composition, growth rate, *etc*. Besides the research of the mechanism of those processes, one of the main aims of the research program was to compare the behaviour of the fuels from different basins under the same conditions during ash deposition. Simultaneous analysis of the results from experimental and real full-scale furnaces would enable prediction of fuel and mineral matter behaviour in real conditions.

Experimental research was carried out with two Serbian coals from Kolubara and Kosovo basins. The influence of the grinding fineness (rest on the sieve over 90 μm is R_{-90} = 30 to 70%), λ = 1.20 to 1.50 and t_w = 450 to 550 °C was analysed. Regime parameters of the furnace were: combustion temperature 900-950 °C and fuel flow-rate 1.68 kg/h. In addition to ash layer thickness measurements, gas temperature measurements, and particle sample extraction have been done. The following analyses of samples have been carried out: screen, proximate and ultimate analysis of fuel, DTA and TGA analyses of coal, laboratory prepared and furnace ash, proximate and mineralogical analysis of the deposits, melting temperature of the deposits, laboratory prepared and furnace ash.

Raw coal dried on air and ground in laboratory mill in different fineness. Analysis of raw and PF coals were given in tab. 1. Investigated coals are lignites with high content of moisture, medium content of ash and low heating value (LHV). The PF samples prepared at laboratory mill are of the same grinding fineness as in power plant. Chemical analysis of laboratory and furnace ash tab. 2 shows that Kolubara ash is aluminosilicate and Kosovo ash besides aluminosilicates has a great percentage of Ca.

Table 1. Proximate analysis (as fired) and ultimate analysis (moisture ash free) of coals

Coal	*W* [%]	*CM* [%]	Ash [%]	I_d [%]	C_{fix} [%]	LHV [kJkg^{-1}]	C [%]	H [%]	O+N [%]	S [%]
Kolubara PF Raw coal	15.52 50.39	52.12 30.60	32.36 19.00	29.14 17.11	22.98 13.49	13.164 6.770	77.52	7.38	14.35	0.75
Kosovo PF Raw coal	11.87 41.13	55.10 36.81	33.03 22.06	27.41 18.31	27.69 18.50	9.664 5.692	62.08	5.65	31.81	0.46

W – moisture, CM – combustible matter, I_d – volatile matter, C_{fix} – fixed carbon

Table 2. Chemical analysis of deposits, laboratory and in-furnace ash

Coal ash type	SiO_2 [%]	Al_2O_3 [%]	Fe_2O_3 [%]	CaO [%]	MgO [%]	Ns_2O [%]	K_2O [%]	SO_3 [%]	t_{synt}[°C]	t_{melt}[°C]
Kolubara 1	55.61	28.41	6.64	3.58	1.54	0.88	0.79	2.53	930	1505
Kolubara 2	53.86	31.59	5.48	2.21	1.37	0.62	1.32	2.97	900	1590
Kolubara 3	38.53	23.01	36.56	1.90	–	–	–	–	1180	1490
Kolubara 4	56.77	27.81	7.98	3.68	0.95	0.48	0.79	1.54	920	1465
Kolubara 5	7,00	–	83.20	2.00	0.67	0.23	0.13	6.05	1000	1405
Kosovo 1	28.49	7.37	6.90	43.63	3.87	0.84	0.57	8.31	1160	1280
Kosovo 2	32.91	6.87	8.05	38.91	3.34	0.63	0.51	8.34	1050	1190
Kosovo 3	24.94	7.24	31.72	36.10	–	–	–	–	1100	1320
Kosovo 4	17.90	5.98	20.46	35.23	3.97	1.28	0.36	14.79	1000	1295
Kosovo 5	30.90	8.22	7.12	43.15	3.42	0.84	0.47	5.87	1150	1305
Kosovo 6	21.30	3.41	8.73	41.03	3.45	0.95	0.27	20.88	1090	1300
Kosovo 7	14.86	3.26	6.62	37.03	2.93	1.02	0.30	33.97	1010	1245

Kolubara: (1) Ash in furnace, (2) Laboratory ash, (3) Front deposits 1 hour, (4) Rear deposits 4 hours, (5) Deposits in real furnace, t_w=550 °C, Kosovo: (1) Ash in furnace, (2) Laboratory ash, (3) Front deposits 30 minute, (4) Front deposits 4 hours, (5) Rear deposits 4 hours, (6,7) Deposits in real furnace, t_w = 450 °C and 550 °C

Growth of deposit formation obtained by combusting Kolubara (KL) and Kosovo (KS) coals are presented in fig. 1. The results were obtained for different probe exposure times (5 minute to 4 hours), different grinding fineness and in the investigated intervals of t_w = 450-550 °C. Growth of front and whole deposit formation obtained by combusting both coals are presented in fig. 2. The results were obtained for different probe exposure times and different excess air in

furnace. The functional dependence is non-linear for both types of coal with permanent growth of deposit weight with time. The obtained deposit quantity for KS coal is remarkably higher.

According to different investigations [5] KS coal shows strong fouling tendency caused by chemical composition of the ash. The initial deposit layer occurs at the frontal side of the tube, being the first phase of the fouling process. After a longer period of probe exposure one notes three types of deposits: front deposits formed by melting of light-fusible ash particles, side deposits formed by very fine ash particles, much thinner than the front ones, rear deposits which are very porous. The chemical analysis of the initial deposit layer tab. 2, shows that CaO and SiO_2 prevail and that it is similar to furnace and laboratory ash. However Fe_2O_3 content is high in it as the consequence of reactions in the layer. In front deposits one notes lowering of Fe content and $CaSO_4$ formation which induces layer hardening. In porous deposits, Fe content is equal as in laboratory and furnace ash, Ca content is slightly higher and SO_3 content is much lower so there is no hardening of these deposits.

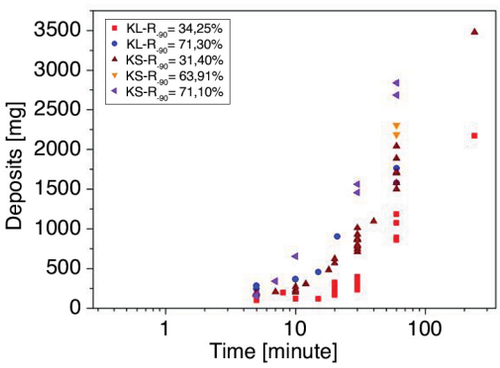

Figure 1. Deposit growth

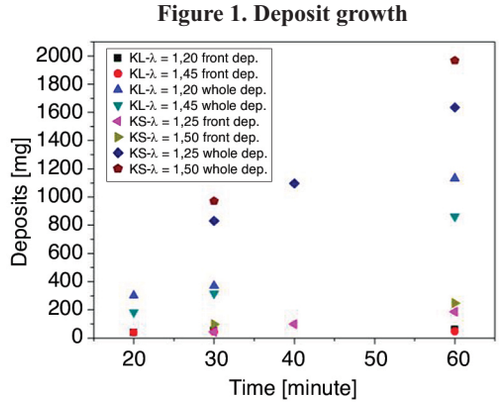

Figure 2. Deposit growth

During the combustion of KL coal, formation of the initial layer has not been noticed, but the front and rear deposits are being formed. Deposition of ash particles occurs by stroke of gas flow to the tube, but the thickness of this layer is much smaller than for the KS coal. Also, possibility of solidification of this layer is small, because of low content of S and Ca.

Analysis of the main influential parameters for deposit formation

The main aim of the research program is collection of data and determination of the criteria for the proper choice of furnace parameters on the basis of characteristics of Serbian low-rank coals and different sorts of biomass. This will enable more efficient operation of power plant furnaces and also obtaining of realistic data to be applied in furnace design.

Wall probe temperature exerts great influence on deposition formation pronounced by the reactions between particles of ash and probe wall in their first contact, and later in the reactions inside the layer of formed deposits. Investigation were performed in range of t_w = 450-550 °C, as is the temperature on the furnace heat exchanger surfaces. Figure 3 shows the influence of t_w on whole deposit formation rate. Experiments have shown that the rise of t_w induces increase in quantity of deposit. This is the expected effect of higher t_w which is suitable for keeping the initial layer in adhesive (viscous) condition with higher content of easily melted eutectics. This is followed by increased possibility of sticking of ash particles from the gas flow. Also t_w increased causes chemical reaction within the deposits *i.e.* creates suitable conditions for sulphatization and deposit hardening. The same effect is noted for both coals. For KS coal t_w causes formation of

initial layer the mass of which decreases with t_w rise. But the whole mass of deposits grows with t_w rise because of the rear deposit formation. For KL coal initial layer is not registered but the mass of deposit also grows with t_w rise.

Figure 4 shows the influence of grinding fineness on the ash deposit formation rate for different probe exposure times. It is evident that the amount of formed deposits grows with rise of grinding fineness (lower value of R_{-90}), primarily caused by deposition of higher amount of finer particles. Up to 30 minute of probe exposure when burning finer KS coal (R_{-90} = 31.40%) almost double amount of deposit is obtained. Later on this difference slowly decreases. The same but more pronounced difference of grinding fineness influence was obtained for KL coal fig. 4.

The main effect of excess air is primarily exerted upon the PF combustion process in furnace. Experiments were performed with KL (λ = 1.20 and 1.45), and KS (λ =1.25 and 1.50), coals fig. 2. Change in λ has not shown the same effect for both coals. For KS coal it is evident that deposit amount rises with λ increasing. Also, growth of deposit mass was noted in the front as well as in the rear part of the probe, as a consequence of low gas velocities in the furnace and narrow range of their variation. For KL PF different effect was obtained fig. 2, *i.e.* amount of formed deposits decreases with the λ rise. This result shows a good matching in comparison with the results obtained by measurements on real plants [5]. Something different results are obtained fig. 5, when the total amount of deposits is reduced to 1 m^3 of gas. It is evident that this amount rises with λ decreasing for both coals. This effect occurs because the minimum amount of air for the stoichiometric combustion of these two coals is different.

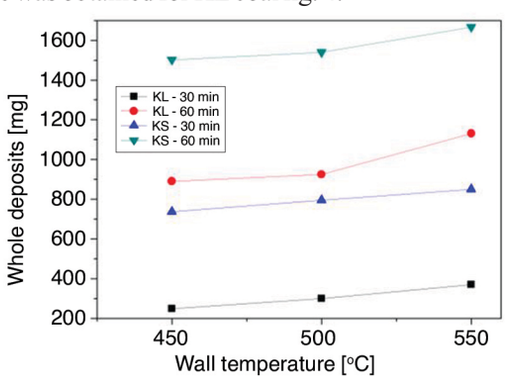

Figure 3. Influence of wall temperature

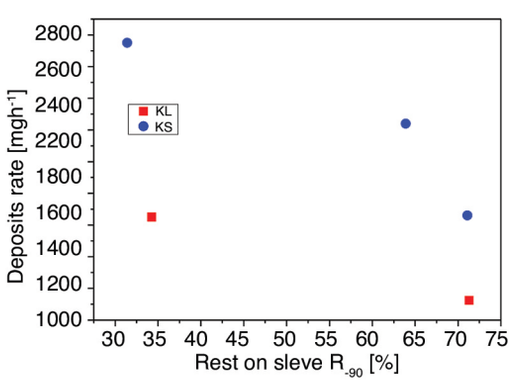

Figure 4. Influence of grinding fineness

Kinetics of ash deposit formation as a function of λ and gas velocity for both coals is presented in fig. 6. The aforementioned influence of λ is clearly remarked here. Gas velocity was being changed in the range 4.24-4.57 m/s for KS PF and 4.78-5.17 m/s for KL PF. For KS PF there is a significant increase in front and whole deposits rate with increasing of gas velocity in a very narrow range. For KL PF a noticeable drop in total deposits and a slight decrease of the front deposits with an increase of gas velocity was observed. Small change in gas velocity realized by change in air intake does not enable making final conclusions and needs further investigation.

Ash related problems during biomass and coal combustion

The reserves of waste biomass from agricultural production in Serbia are very abundant [6]. Base on this fact at the Vinča Institute in Belgrade great efforts have been made to develop a clean technology for utilizing baled biomass for energy production. As a result a technology for

cigarete type combustion of balled biomass has been developed. Experimental investigation of biomass combustion in the boiler with thermal power of 1.5 MW was carried out over a long period of time [6, 7]. During the tests conducted, combustion of soybean, rapeseed and wheat straw and maize (cornstalks) has been analysed. Tests were carried out using the bales of straw. Proximate analysis of biomass varieties used in the tests conducted is presented in the tab. 3.

Moisture and ash content determined in each of the fuel types examined were found to vary significantly. Content of combustible and volatile matters were determined to be quite high. Heating values of biomass samples were determined to be quite high and close to heating value of coal. Ash melting temperatures were observed to differ between the ranges of biomass samples analysed. Temperatures determined for the case of soybean and rapeseed straw combustion were found to be quite high, leading to the conclusion that no problems are to be expected in plants where there types of biomass are used. On the other hand, temperatures associated with wheat and maize straw combustion were found to be rather low, indicating that problems associated with ash particle adherence to the furnace walls may be encountered during combustion of these biomass varieties.

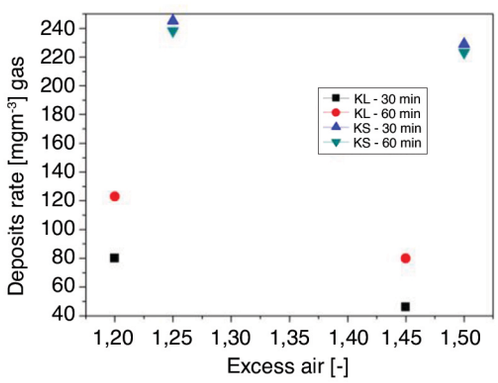

Figure 5. Influence of excess air, t_w = 550°C

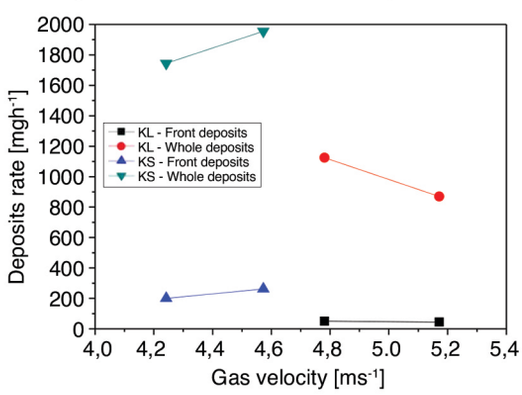

Figure 6. Influence of gas velocity

Table 3. Proximate analyse of agricultural biomass (dry base)

Value	Units	Type of straw			
		Soybean	Rapeseed	Wheat	Maize
Total moisture	%	8.35-39.95	8.84-18.19	8.28-9.90	7.26-9.79
Ash	%	3.92-15.82	3.95-5.88	5.89-12.53	2.26-7.22
Sulphur total	%	0.17-0.36	0.23-0.24	0.21-0.22	0.28-0.30
Sulphur in ash	%	0.07-0.23	0.04-0.05	0.11-0.12	0.07-0.09
Sulphur combustible	%	0.07-0.023	0.18-0.19	0.08-0.09	0.21-0.22
Char	%	18.60-30.94	22.47-23.76	24.04-30.82	19.33-23.48
Fixed carbon	%	14.06-20.27	17.88-18.52	18.15-18.29	14.45-17.95
Volatile matter	%	69.06-81.40	76.24-77.53	69.18-75.96	76.52-80.67
Combustible matter	%	83.95-96.40	94.12-96.05	87.47-94.11	94.48-97.23
LHV	MJ/kg	16.4-18.6	17.7-17.9	16.1-17.0	17.0-17.9
Temperature		Ash melting temperatures			
Shrinkage starting, t_1	°C	1185	1100	880	1010
Deformation, t_2	°C	1310	1270	920	1040
Hemisphere, t_3	°C	1420	1400	1100	1075
Flow, t_4	°C	1450	1420	1160	1100

One of the very important parameters of any biomass combustion process is the ash shrinkage starting (sintering) temperature. This is the temperature at which shrinking of the ash occurs *i.e.* the temperature when ash starts to exhibit a tendency towards slagging. In a facility with no liquid slag removal system, temperatures developed in the combustion chamber must not exceed values that might lead to ash slagging. One of the particularly unfavourable features associated with agricultural biomass combustion considers the fact that ashes produced by biomass combustion exhibit a strong slagging tendency. This means that sintering temperature of ash residue produced by agricultural biomass combustion is much lower than the respective temperature associated with combustion of forest biomass [8]. This phenomenon is not accidental but rather the result of artificial fertilizer use in the cultivation of agricultural crops. The use of artificial fertilizers entails increased levels of potassium in the mineral-storing parts of the plant (which convert to ash). On the other hand, one of the main components contained in the mineral parts of the plant is SiO_2 - quartz sand. Melting temperature of SiO_2 equals 1400-1500 °C, but with an addition of potassium or sodium the temperature can be lowered to below 800 °C. This is also the main cause of the pronounced ash slagging tendency associated with agricultural biomass combustion in power units.

Ash related operational problems have always been a key issue in energy conversion processes that utilise solid fuels, *e.g.* in conventional combustion and gasification processes. The problems arise from the behaviour of the inorganic matter, *i.e.* non-combustible matter, at high temperatures, and comprise slagging, fouling, bed agglomeration as well as corrosion of vital parts of conversion process equipment. Common solid fuels for thermal energy conversion are anthracite, pet coke, bituminous coals and sub-bituminous coals, lignites or brown coal, peat and various types of biomass fuels, *e.g.* agricultural and wood-based fuels, as well as various types of waste fuels. Coal is by far the dominant solid fuel source for heat and power generation worldwide, and because of this, many of the present fuel characterisation methods have been developed for coal. With respect to ash-related operational problems with coal fired boilers, the behaviour of coal mineral matter has been extensively studied and many of the fundamental underpinnings of the slagging and fouling phenomena in coal fired boilers have been worked out over the years. However, despite the high degree of insight into the mechanisms of ash deposition, slagging, fouling, corrosion and fuel blending continue to be the leading coal quality concerns of the personnel at the power industry [9].

Comparing the inorganic matter in coal and biomass, it is clear that the modes of occurrence, *e.g.* the manner in which an element is chemically bound to the inorganic or organic constituents of the fuels, are different. The most abundant inorganic species in coal are alumina-silicate clay minerals which, together with quartz, comprise between 60-90% of the total mineral matter. The inorganic material in biomass can be divided into two fractions: adventitious materials that are added to the fuel during fuel processing, *e.g.* sand or clays from harvesting, storage *etc.* and inherent material, which acts as nutrients with essential biological functions for the plants and is more intimately distributed (atomically dispersed) throughout the fuel [10, 11]. Due to their different modes of occurrence the behaviour of the inherent and adventitious materials at high temperature differs, but both types of materials are known to play a significant role in the ash transformation mechanism at elevated temperatures. However, with respect to ash-related operational problems during biomass combustion the inherent material, comprising the elements Si, Ca, Mg, K, Na, P, S, Cl and Al, is the primary source responsible for slagging, fouling and corrosion.

Comparing the ash-related operational problems between coal and biomass, in general, they will be more severe in biomass-fired boilers due to the formation of compounds with lower

ash melting temperatures, as a result of several types of reactions in which alkali plays a central role [12]. Examples of principal ash transformation processes that occur during elevated temperatures include [13]: reactions between silicon and other elements chiefly alkali and alkaline earth metals, volatilisation of alkali and heavy metals, and volatilisation or release of chlorine and sulphur. Experience from fixed and fluidised bed combustion shows [14] that alkali and silicon (the main ash constituent of wheat straw), will react to form a silicate-based slag melt, thus preventing K to reach the gas phase. The addition of Ca, *e.g.* from woody biomass, to such a melt has been shown to be beneficial, as it will react and form compounds with higher melting temperatures. In a PF flame, a prerequisite for this type of reaction is that the Si-K rich (straw) particle will have to: physically collide with a Ca-rich (woody biomass) particle and be given enough residence time, so that this type of reaction can take place [13]. Other potential reaction phenomena that result in alkali being prevented from reaching superheaters are that alkali compounds in the post flame region (~1200 °C) deposit on larger fly ash particles, which are then entrained by the flue gas ending up in the electrostatic precipitator or flue gas cleaning filters. Co-firing of biomass and coal has been shown to reduce ash-related operational problems, primarily due to positive interactions between clay minerals and/or S in coal and alkali in biomass, but industrial practice also shows that the maximum biomass co-firing proportions that can be used in coal fired boilers for a non-biased boiler performance are relatively low, 10-20% on mass basis [15].

With respect to conversion of agricultural fuels, chiefly wheat straw, into heat and power, a large practical experience base has been built-up in many country [13]. Being an agricultural industry by-product, wheat straw has several benefits compared to other agricultural fuels, primarily as it does not compete with arable land for food production. Ash-related operational problems arising from the use of wheat straw are very problematic [12] and this causes frequent shutdowns of boilers. Therefore, for wheat straw, as well as other agricultural fuels, to be successfully introduced as a (co-firing) fuel in dedicated high efficiency biomass-fired boilers, issues concerning ash-related operational problems need to be addressed and solved without using fossil fuels (hard coal) as co-firing fuel.

Key empirical correlations for slagging and fouling

There are numerous empirical correlations for the assessment of ash behaviour and their possible effects on deposition, both on the furnace walls (slagging) and on convection tube banks (fouling) [1, 2, 16-19]. Based on an extensive database composed of Serbian coals and by correlative analysis of the existing semi-empirical criteria, indicators of the tendency of domestic coals to create deposits on heating surfaces have been developed. The key empirical correlations developed for domestic coal are [4, 16, 19]: the interval between the initial deformation (t_1) and fluid (t_3) temperatures - if the interval is small, a thin, liquid layer of slag will be created on the furnace walls extremely difficult to control by soot blowing; otherwise, with the growth of the interval, bond between the tube and the deposits becomes weaker and deposits can be easily removed by soot blowing and indicators for slagging and fouling based on ash composition.

Indicators for slagging based on ash composition, tab. 4, can be defined as [8, 16, 18, 19]:

- Base number (%): $B = Fe_2O_3 + CaO + MgO + Na_2O + K_2O$
- Acid number (%): $A = SiO_2 + Al_2O_3 + TiO_2$
- Base to acid ratio (-): B/A
- Fusibility index (-): $It = (SiO_2 + Al_2O_3) / (Fe_2O_3 + CaO + MgO + Na_2O + K_2O)$
- Silica ratio (%): $So = SiO_2 * 100 / (SiO_2 + Fe_2O_3 + CaO + MgO)$ for coal ashes that contain $Na_2O \leq 2.5\%$ or $CaO \leq 7.5\%$.

Table 4. Indicators for slagging based on ash composition (suggested limits) [16]

Indicator	High slagging	Medium slagging	Low slagging
Base number (%)	34-67	17-34	<17 and > 67
Base to acid ratio (–)	0.64-3.5	0.24-0.64	<0.24 and >3.5
Fusibility index (–)	0.20-1.5	1.50-4.60	<0.2 and >4.6
Silica ratio (%)	21-50	50-78	<21 and >78

Correlative analysis of the tested coals yielded the correct functional dependence of the criteria B, B/A, It, and So previously defined are defined in [16]. The limits for the application of these criteria are in accordance, and therefore any of these four criteria can be used for the assessment of the slagging tendency of domestic lignites.

According to the ASTM standard [20] two different types of ash can be distinguished: Bituminous ash type (ash with an acid reaction): $(CaO + MgO) < Fe_2O_3$ or alternatively $SiO_2 > (Fe_2O_3 + CaO + Na_2O)$ and Lignitic ash type (ash with a base reaction): $(CaO + MgO) > Fe_2O_3$ or alternatively $SiO_2 < (Fe_2O_3 + CaO + Na_2O)$.

Indicators for fouling based on ash composition, tab. 5, can be defined [16, 20]:

(1) Sodium content in ash (%): Na_2O

(2) Total alkali content of coal ash (%): $Na_2O_\Sigma = Na_2O + 0.6589*K_2O$

(3) Total alkali content on coal (%): Na_2O_{eq} of coal = $(Na_2O + 0.6589*K_2O)*Ash/100$ (Application: coals with bituminous type ash)

(4) Fouling factor (%): $R_f = (B/A)*Na_2O$ (Application: bituminous type ash)

(5) Chlorine content of coal (%): Cl.

As an appropriate criterion for the assessment of coal fouling potential, the criterion *total alkali content in the ash* should be taken, because it takes into account the influence of K_2O (potassium oxide) on the fouling process.

Table 5. Indicators for fouling based on ash composition

Indicator	Low slagging	Medium slagging	High slagging	Severe slagging
(1,2) Bituminous coal ash	<2	2-6	6-8	>8
(1,2) Lignitic coal ash	<0.5	0.5-1	1-2.5	>2.5
(3)	<0.3	0.3-0.45	0.45-0.6	>0.6
(4)	<0.2	0.2-0.5	0.5-1	>1
(5)	<0.2	0.2-0.3	0.3-0.5	>0.5

Practical application of fouling/slagging indicators

The results of the application of fouling/slagging indicators for the chemical composition of coal and biomass ash show the next. As Serbian coal slagging indicators were obtained from the database in which 88% constitutes of lignitic-type-ash coals [16], that their application to biomass fuels with a lignitic-like ash type should confirm the tendency of this fuel to create deposits on the boiler heating surfaces. The results of the aforementioned criteria for assessing the propensity of coal to fouling and slagging were applied to two laboratory obtained ash of KL and KS coals, tab. 2, and to laboratory ash of several types of biomass [2, 10, 11, 12, 17, 18, 21, 23], tab. 6.

Based on the applied indicators it can be concluded, tab. 7; KL coal has a bituminous ash type (B) and has no tendency to slagging nor to fouling the heating surfaces; KS coal has a lignitic (L) type of ash and shows a pronounced tendency to slagging and a moderate tendency to fouling the heating surfaces; all biomass tested has a lignitic (L) type of ash, wheat straw-soaked, switch-grass, and wood residue show a moderate tendency to slagging, while the oak wood is at

Table 6. Chemical analysis of biomass laboratory ash

Biomass ash type	SiO_2 [%]	Al_2O_3 [%]	TiO_2 [%]	Fe_2O_3 [%]	CaO [%]	MgO [%]	Na_2O [%]	K_2O [%]	P_2O_5 [%]	SO_3 [%]	Ash [%]
(1)	43.48	2.98	0.18	1.18	5.65	3.05	12.74	22.32	1.78	6.62	12.78
(2)	69.56	3.21	0.05	1.82	6.57	2.67	3.92	6.54	3.77	1.89	6.45
(3)	50.35	1.54	0.09	0.88	8.21	2.74	3.52	24.89	3.54	4.24	12.78
(4)	49.95	5.06	0.29	2.53	14.73	4.49	0.16	18.53	2.42	1.84	-
(5)	37.79	4.69	0.24	2.17	12.03	4.45	0.72	26.84	6.14	4.93	-
(6)	50.78	0.67	0.08	0.95	9.89	2.87	1.39	28.18	2.97	2.22	-
(7)	40.80	5.45	0.29	2.00	30.68	2.00	0.44	13.45	2.22	2.67	-
(8)	33.70	3.10	0.10	3.80	15.40	7.90	1.30	30.40	3.20	1.10	-
(9)	23.66	8.75	0.15	4.27	15.31	7.33	0.8	28.53	7.13	4.07	-
(10)	66.73	4.62	0.25	2.08	5.73	3.07	0.59	11.88	4.61	0.45	8.97
(11)	66.25	2.22	0.28	1.36	10.21	4.71	0.58	9.64	3.92	0.83	8.97
(12)	23.15	5.75	1.20	3.27	37.35	7.26	2.57	11.59	2.90	4.95	-
(13)	53.15	12.64	0.57	6.24	11.66	3.06	4.47	4.85	1.37	1.99	-
(14)	12.40	0.12	0.10	1.10	68.19	11.50	0.90	2.60	2.30	0.80	-
(15)	29.93	4.27	0.39	4.20	15.56	5.92	2.00	31.99	1.90	3.84	-
(16)	48.95	9.49	0.10	8.49	17.48	1.10	0.50	9.49	1.80	2.60	-

(1) wheat straw-untreated, (2) wheat straw-soaked, (3) wheat straw, (4) corn straw, (5) oat straw, (6) barley straw, (7) rape straw, (8) hazelnut shells, (9) sunflower husks, (10) switch-grass, (ll) switch-grass, (12) wood, (13) wood residue, (14) beech bark, (15) oak sawdust, (16) oak wood

Table 7. Assessment of the slagging/fouling tendency

Fuel	B	B/A	It	So	Ash type	Na_2O	Na_2O_Σ	Na_2O_{eq}	R_f
	Slagging					Fouling			
Kosovo	51.67	1.29	0.77	-	L	0.63	0.97	-	-
Kolubara	11.06	0.13	7.77	85.60	B	0.62	1.50	0.33	0.08
(1)	44.94	0.96	1.03	-	L	12.74	27.45	-	-
(2)	21.52	0.30	3.38	-	L	3.92	8.23	-	-
(3)	40.24	0.77	1.29	-	L	3.52	19.92	-	-
(4)	40.44	0.73	1.36		L	0.16	12.37	-	-
(5)	46.21	1.08	0.92		L	0.72	18.40	-	-
(6)	43.28	0.84	1.19	-	L	1.39	19.96	-	-
(7)	48.57	1.04	0.95	-	L	0.44	9.30	-	-
(8)	58.80	1.59	0.63	-	L	1.30	21.33	-	-
(9)	56.24	1.73	0.58	-	L	0.80	19.60		-
(10)	23.35	0.33	3.06	85.98	L	0.59	8.42	-	-
(11)	26.50	0.39	2.58	80.27	L	0.58	6.93	-	-
(12)	62.05	2.06	0.47	-	L	2.57	10.21	-	-
(13)	30.28	0.46	2.17	-	L	4.47	7.67	-	-
(14)	84.28	6.68	0.15	13.30	L	0.90	2.61	-	-
(15)	59.67	1.73	0.57	-	L	2.00	23.08	-	-
(16)	37.06	0.63	1.58	-	L	0.50	6.75	-	

Slagging/fouling tendency - low medium high severe (1)-(16): Biomass laboratory ash same as in tab. 6

the boundary of the tendency toward pronounced and moderate slagging; the beech bark has no tendency to slagging, all other biomass shows a strong tendency towards slagging; as biomass ash is characterized by the high content of K_2O, and as it is as a rule with lignite type of ash, the only criterion for estimating the propensity of this type of fuel is total alkali content of coal ash-Na_2O_Σ.

Taking this into account and as expected on the basis of the foregoing, all examined biomass indicates a serious propensity for heavy fouling of convective heating surfaces.

Conclusion

Investigation of ash deposit processes in laboratory condition performed with two different PF has shown that temperature of the probe has a great influence on the ash deposit process. This influence is especially pronounced in the reactions between particles of ash and probe walls in the first contact, and later in the reactions inside the layer of formed deposits. Investigation of the influence of grinding fineness of PF has shown that the increase of PF fineness cause rise of the quantity of deposits. Change of excess air value has shown different influence on deposit formation rate for each investigated fuel. The results of the practical application of fouling/slagging indicators for the chemical composition of coal and biomass ash show the next. As Serbian coal slagging indicators were obtained from the database in which 88% constitutes of lignitic-type-ash coals, that their application to biomass fuels with a lignitic-like ash type should confirm the tendency of this fuel to create deposits on the boiler heating surfaces, showing an exceptional tendency towards heavy fouling of convective heating surfaces.

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References

[1] Repic, B., *et al*., Investigation of Rate of Ash Deposit Formation on Heat Transfer Surfaces of Boilers, *Proceedings*, Industrial Furnaces and Boilers, Rio Tinto, Portugal, 1995, Vol. 1, pp. 229-237
[2] Werther, J., *et al*., Combustion of Agricultural Residues, *Progress in Energy and Combustion Science*, *26* (2000), 1, pp. 1-27
[3] Saidur, R., *et al*., A Review on Biomass as Fuel for Boilers, *Renewable and Sustainable Energy Reviews*, *15* (2011), 5, pp. 2262-2289
[4] Repić, B., Kinetics of the Ash Deposit Formation of the Convective and Irradiated Surfaces in the Boiler Furnaces Using Pulverized Coal, (in Serbian), MSc. Thesis, University of Belgrade, Belgrade,1979
[5] Savić, D., *et al*., Investigation of Tendencies of the Lignites from the Kolubara, Kostolac and Kosovo Basins Towards Formation of Deposits on Heat Transfer Surfaces During Combustion in Boiler Furnaces, Bulletin LXV de l'Academie Serbe des Sciences et des Arts, Classe des Sciences techniques, No 15., pp. 21-46, Belgrade, 1979
[6] Repic, B. *et al*., Investigation of the Cigar Burner Combustion System for Baled Biomass, *Biomass and Bioenergy*, *58* (2013), 11, pp.10-19
[7] Mladenović, R., *et al*., The Boiler Concept for Combustion of Large Soya Straw Bales, *Energy*, *34* (2009), 5, pp. 715-723
[8] Pronobis, M., Evaluation of the Influence of Biomass Co-Combustion on Boiler Furnace Slagging by Means of Fusibility Correlations, *Biomass and Bioenergy, 28* (2005), 4, pp. 375-383
[9] Harding, N. S., O'Connor, D. C., Ash Deposition Impacts in the Power Industry, *Fuel Processing Technology*, *88* (2007), 11-12, pp. 1082-1093
[10] Jenkins, B. M., *et al*., Combustion Properties of Biomass, *Fuel Processing Technology*, *54* (1998), 1-3, pp. 17-46
[11] Vassilev, V. S., *et al*., An Overview of the Chemical Composition of Biomass, *Fuel*, *89* (2010), 5, pp. 913-933
[12] Baxter, L. L., *et al*., The Behavior of Inorganic Material in Biomass-Fired Power Boilers: Field and Laboratory Experiences, *Fuel Processing Technology*, *54* (1998), 1-3, pp. 47-78
[13] Nordgren, D., Experimental Studies of Pulverised Biomass Combustion - Impacts on Ash Transformations and Process Temperature, Ph. D. Thesis, Lulea University of Technology, Lulea, Sweden, 2011
[14] Ohman, M., *et al*., Slagging Tendencies of Wood Pellet Ash During Combustion in Residential Pellet Burners, *Biomass and Bioenergy*, *27* (2004), 6, pp. 585-596

[15] Hansen, K. W., *et al*., Cofiring Coal and Straw in a 150 MWe Power Boiler Experiences, *Biomass and Bioenergy*, *19* (2000), 6, pp. 395-409
[16] Mladenović, M., *et al*., Criteria Selection for the Assessment of Serbian Lignites Tendency to Form Deposits on Power Boilers Heat Transfer Surfaces, *Thermal Science*, *13* (2009), 4, pp. 61-78
[17] Vamvuka, D., Zografos, D., Predicting the Behaviour of Ash from Agricultural Wastes During Combustion, *Fuel*, *83* (2004), 14-15, pp. 2051-2057
[18] Gudka, B., *et al*., A Review of the Mitigation of Deposition and Emission Problems During Biomass Combustion Through Washing Pre-Treatment, *J Energy Inst*, *89* (2016), 2, pp. 159-171
[19] Mladenović, M., Choice of Criteria for the Assessment of Tendency of Domestic Lignites Towards Deposit Formation on Power Boilers Heat Transfer surfaces (in Serbian), MSc Thesis, University of Belgrade, Belgrade, 2005
[20] Winegartner, E. C., Coal Fouling and Slagging Parameters, ASME Research Committee on Corosion and Deposits from Combustion Gases, ASME, USA, 1974
[21] Vamvuka, D., *et al*., Evaluation of Ashes Produced from Fluidized Bed Combustion of Residues from Oranges' Plantations and Processing, *Renewable Energy, 72* (2014), Dec., pp. 336-343
[22] Jenkins, B. M., *et al*., On the Properties of Washed Straw, *Biomass and Bioenergy*, *10* (1996), 4, pp. 177-200
[23] Marinković, A., *et al*., Characteristics of Agricultural Biomass Exposed to the Process of Leaching and Washing (in Serbian), *Contemporary Agricultural Engineering*, *39* (2013), 4, pp. 229-236

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