

FOULING AND ITS MITIGATION IN PC BOILERS CO-FIRING FORESTRY AND AGRICULTURAL BIOMASS

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ABSTRACT

This paper presents a study of the fouling properties of solid fuels based on analyses of ashes from hard coal, forestry biomass and agricultural biomass, ash deposits collected directly from the boiler surfaces and ash deposits collected from a deposition probe. All samples were collected in the area of the steam superheater/reheater of the OP 380 pulverized-coal boiler co-firing forestry and agricultural biomass. In addition, the study concerns mitigation of unwanted fouling through application of a silica-based fireside additive. An analysis was carried out to obtain the following information:

- physical and chemical properties of ash produced during co-firing of a biomass mixture (50 wt.% forestry/50 wt.% agricultural biomass) and coal in order to determine its propensity for fouling and slagging without the use of a fireside additive;
- slagging/fouling indices during co-firing of a biomass mixture (50 wt.% forestry/ 50wt.% agricultural biomass) and coal with the use of a fireside additive;
- slagging/fouling indices during co-firing of pure agricultural biomass (sunflower husk) and coal with the use of a fireside additive.

The mass flow of co-fired biomass fuel supplied to the boiler during reference measurements and when the additive was fed was the same and amounted to 33 wt.% of the total fuel mass flow.

Finally, the effectiveness of fouling mitigation is determined by comparing the results of the deposition rate obtained with the use of a deposition probe for all three cases of co-firing.

INTRODUCTION

Co-combustion of biomass in power boilers designed for coal firing causes a decrease in the mass flow of ash. On the other hand, operational experience indicates that there is an increased fouling of heating surfaces of the boiler and its flue gas duct, which has an adverse effect on the economic

effectiveness of the machine operation [1]. The creation of both high-temperature deposits in the furnace chamber area and medium-temperature deposits in convection ducts causes the following:

- a reduction in the boiler efficiency due to the rise in exhaust flue gas temperature,
- a reduction in the power unit efficiency due to the decrease in the heat exchange rate, which necessitates increased mass flows of fuel to maintain steam parameters,
- a reduction in the efficiency of dust collection in the electrostatic precipitator,
- an increase in the consumption of energy needed to force flue gases and air through the boiler,
- a rise in CO₂ emissions per unit of effective heat.

In some cases ash deposits become so large that the boiler has to be shut down so that the heating surfaces or the flue gas ducts can be cleaned. All these phenomena result in higher operating costs of the boiler.

One available solution that allows a reduction in the size of deposits is the application of cleaning devices (such as blowers). This upgrade, however, calls for higher expenditures on the installation and operation of blowers and involves increased wear of the cleaned surfaces due to erosion and extra stress that arises. In order to determine the optimum characteristic of the operation of devices blowing off deposits, it is also necessary to investigate the deposition rate in certain areas of the boiler; this rate is most affected by the properties of the ash produced during combustion [2].

In the fluidized bed technology it is common to use sorbents added to the inert bed material which, on coming into contact with ash particles, modify the ash characteristics leading for example to the formation of eutectics featuring a higher fusion temperature [3]. This solution is used more and more often by users of pulverized-fuel boilers. A task to solve is to select the method and the place where the sorbent is to be fed into the pulverized-fuel boiler to ensure its

proper mixing with the ash constituents and a maximum contact time.

Being fired in power boilers, the mineral matter contained in fuel is transformed partially into fly ash, which forms ash deposits on heating surfaces (steam reheaters/superheaters, air preheaters and economizers). The chemical composition of the mineral fraction and the processes related to the fuel preparation and combustion decide about the properties of created fly ash (chemical composition, grain size) which later have an impact on the intensity of the fouling phenomena and erosion.

According to classification [4], an essential feature of medium-temperature deposits on convection surfaces is its looseness, as this is the quality which makes it possible to remove deposits with appropriate devices. The composition of these deposits is very similar to the oxide composition of fly ash, as opposed to high-temperature deposits which solidify gradually and which are thus very different from medium-temperature deposits. The value of the B/A factor is often assumed as the parameter that characterizes the ash tendency to form deposits:

$$B/A = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O + (P_2O_5)}{SiO_2 + Al_2O_3 + TiO_2} \quad (1)$$

This factor was introduced for ashes arising from fossil fuels with a very low content of phosphorus, which therefore was usually ignored in formula (1). However, the impact of this element on the ash fluxing temperature and on the tendency to cause deposition on convection surfaces is important when burning biomass fuels and depends on the form in which the element is contained in ash. If it is the content of phosphorus pentoxide that is significant, a stronger tendency of the ash with a higher content of P_2O_5 (or P_4O_{10} in fact) to form deposits on the tubes of the boiler convection part has to be feared [5-7]. The conclusion is that higher values of the B/A factor should correspond to ashes of this type and that the P_2O_5 content should be introduced into the nominator. This is of special importance in the case of combustion or co-combustion of biomass with a high content of phosphorus.

Ashes created during the co-firing of biomass feature a high content of alkaline compounds and, consequently, much lower fusion temperatures and a stronger tendency to cause fouling of the boiler heating surfaces compared to ashes arising from coal combustion. One of the most important questions is whether the ashes created during co-firing of biofuels feature characteristics more similar to biomass ashes or to those arising from the combustion of coal, or whether they behave like ashes from the combustion of a mixture. Which of these possibilities is closer to reality determines the way in which the known fouling/slagging indices such as the B/A factor or others are used [6, 7].

At present, the most common biofuels in power boilers intended for co-firing of biomass are deciduous wood chips, sawmill dust, by-products of agricultural origin such as varieties of straw and even crop grains, sunflower husks, fruit and olive cake, etc. All of them are characterized by ashes with a strong tendency to cause fouling of the boiler

heating surfaces. Therefore, it is becoming more and more important to select sorbents that would be able to modify the ash properties during the combustion process.

The measure of the impact of the applied sorbent on the change in chemical properties of deposits assumed in this paper is the determination of the ratio of the degree of thermal efficiency Ψ_z of a bank in the reference state (combustion of coal and biomass with no additive) to that in the comparative state (in particular combustion of coal and biomass with the ComCAT® additive [8], later referred to as CC) calculated based on the B/A factor [9]:

$$\frac{\Psi_{z\ sample}}{\Psi_{z\ ref}} = \left(\frac{B/A_{sample}}{B/A_{ref}} \right)^{-0.354} \quad (2)$$

where: B/A_{sample} – fouling factor for given sample,

B/A_{ref} – fouling factor when coal and biomass are co-fired with no additive (reference state).

EXPERIMENTAL DETAILS & MATERIALS

Sampling ports

Samples of deposits collected both directly from the heating surfaces of the OP 380 pulverized-fuel boiler with a steam output of 380 t/h and at places shown in Fig. 1 were analyzed.

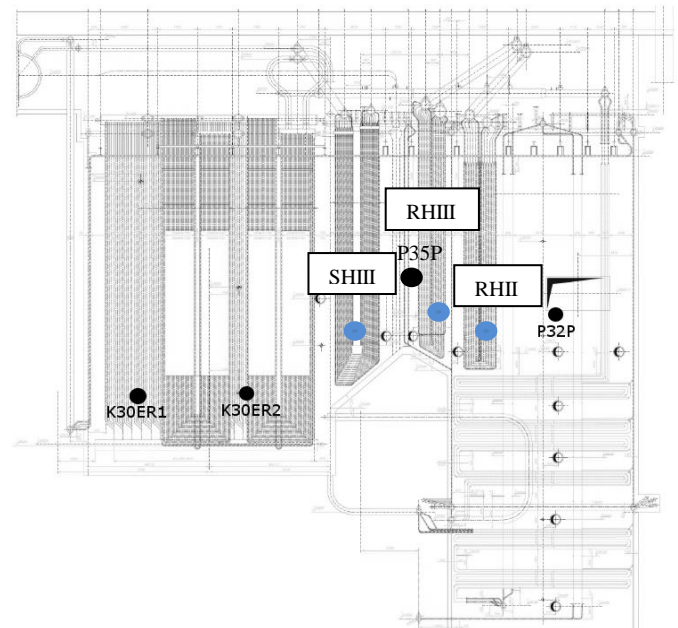


Fig. 1 Sampling ports: SH III, RH III and RH II (deposits from superheaters/reheaters) and P35P, P32P (samples taken by the deposition probe)

During a site inspection of a shut down OP 380 pulverized-fuel boiler, the state of deposits on the heating surfaces was assessed and 3 samples were collected from deposits on the tubes. The following deposits were analyzed (Fig. 1):

- on the III stage of live steam superheater, sample marking: SH III,
- on the III stage of steam reheater, sample marking: RH III,
- on the II stage of inter-stage steam reheater, sample marking: RH II.

For the testing with the use of a deposition probe, access windows were used in the side waterwalls of the K2 boiler furnace chamber at the level of 34.8 m ($\varnothing 120\text{mm}$) marked in Fig. 1 as P35P. The measuring points are located in the outlet cross-section of the aerodynamic narrowing of the horizontal draft duct, between the III stage of the live steam superheater (SH III) and the III stage of steam reheater (RH III). Reference measurements were carried out in a different area of the boiler at the level of 32.0 m in the second duct over the convective superheater at the place marked in Fig. 1 as P32P.

Deposition probe

The measurement of the deposition rate in the area of superheaters/reheaters \dot{m}_{DP} [$\text{g}/\text{m}^2\text{h}$] is performed using a deposition probe ($\varnothing 33 \times 2.5 \text{ m}$) – Fig. 2, cooled with compressed air (from a 6.0 atm compressed air installation) so that the measured temperature of the metal of the probe wall corresponds to the operating temperature of the metal of the tubes of the analyzed superheater/reheater.

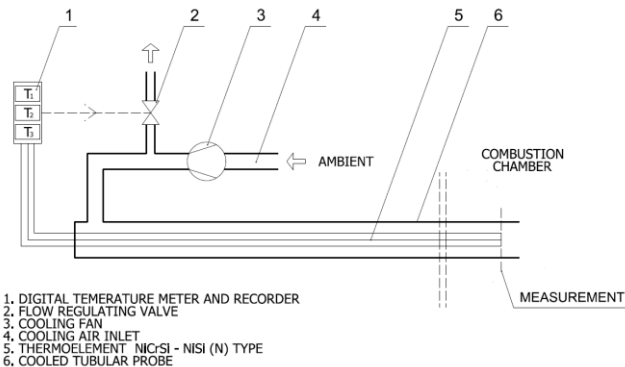


Fig. 2 Diagram of the deposition probe measuring path $\varnothing 33 \times 2.5 \text{ m}$.

The probe is inserted into the boiler flue gas ducts through measuring stub pipes placed in the waterwalls at the level of the superheaters/reheaters. A change in the deposit mass (and in its chemical composition) in the area of the boiler duct under analysis for identical times of exposure but for different types of fuel (during the combustion of coal only, during the co-firing of biomass and when sorbents reducing slagging are added to the fuel) is the basis for the assessment of the impact of biomass and the sorbent addition on the change in the rate at which deposits are formed on the superheater/reheater tubes. Also, the composition and the grain size of the fly ash collected from the electrostatic precipitator were analyzed.

When the deposition probe was put in place (actively – 2.0 m deep into the flue gas duct) in the inspection manhole opening in the area of the analyzed superheater/reheater and

after the metal surface temperature stabilized – after being cleaned – the probe was exposed in cycles of $\tau_1=1$, $\tau_2=3$ and $\tau_3=6$ hours. After each such cycle, the deposit accumulation was measured – the deposits were collected from the probe surface and weighed.

The deposition rate (deposit mass flow density \dot{m}_{DP}) and the efficiency of deposit formation were determined

$$\eta_D = \frac{\dot{m}_{DP}}{\dot{m}_{Fash}} \cdot \frac{A_F}{A_{DP}} \quad (3)$$

where:

\dot{m}_{DP} – deposit mass flow density (deposition rate), $\text{g}/\text{m}^2\text{h}$

\dot{m}_{Fash} – mass flow density of the ash washing the heating surfaces in the flue duct cross-section under analysis, $\text{g}/\text{m}^2\text{h}$

A_F – surface area of the flue duct cross-section under analysis, m^2

A_{DP} – the deposition probe inflow surface area, m^2

Fuel properties

In order to obtain results illustrating the impact of the fuel characteristics (type of coal, kind of forest biomass with a content of agro biomass) and of the used additive on the chemical composition of formed deposits, coal and biomass samples were taken for further analysis during the measurements. The mass content of co-fired biomass in the mass flow of the fuel fed into the boiler during the measurements, both reference measurements and those performed when the sorbent was added, was identical and amounted to 33 wt.%.

Table 1. Characteristics of coals and additional fuels used for the testing (W/W1 – hard coal, B1 – 50/50 mixture of forest biomass pellets and sunflower husk pellets, B2 – 100% sunflower husk pellets)

	Unit of measure	no additive		with additive		
		W	B	W1	B1	B2
Q_i^r	kJ/kg	26,499	17,869	31,136	17,246	16,972
A^r	%	10.3	0.7	6.4	2.8	5.8
V^{daf}	%	35.4	83.9	25.4	78.5	79.4
W^r_t	%	7.6	6.0	3.4	7.9	5.9
C_t	%	65.22	49.33	79.78	46.35	45.56
H_t	%	4.01	5.72	4.37	5.54	5.55
N^r	%	0.74	0.14	0.88	0.51	1.02
S_t	%	0.37	0.02	0.42	0.10	0.17
O^r	%	11.70	37.93	4.73	36.72	35.90
Cl^r	%	0.004	0.132	0.082	0.029	0.091

Oxide analyses were conducted of the deposit samples collected from the deposition probe and from the boiler heating surfaces. They were then compared to the composition of the fly ash from the electrostatic precipitators (POP1, POP2).

The performed measurements made it possible to determine the fouling factors for the reference conditions

(co-firing of coal and biomass) and for the conditions when the additive was used.

RESULTS

Superheater/reheater deposits

It can be seen in Fig. 3 that sintered deposits occurred on the tubes of the final live steam superheater (SHIII) with a size and shape typical of boilers fired with pulverized hard coal. The festoon of the boiler proper after SHIII did not feature significant fouling, either.

The degree of fouling of the final steam reheater (RHIII) was much bigger. It was composed of slightly sintered deposits, quite large at times, on the inflow surface of the tubes.

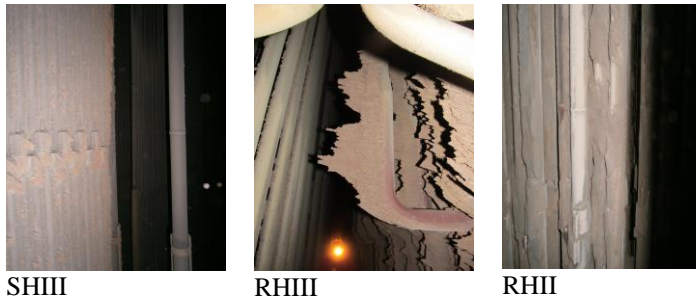


Fig. 3 Shape of deposits on the surfaces of the steam superheater and reheater

The part most affected by fouling was the countercurrent flow bank of the II stage steam reheater RH II. Due to a lower temperature of flue gases and steam in this area, the deposits on the tubes were of a typical, loose medium-temperature nature. The extremely strong fouling of these surfaces is probably caused by the structure of this particular area. There is a chance that flue gases may bypass the bank taking the shortest route through the gap in the fire bridge.



Fig. 4 Gap below RH II reheater – the area facing fly ash erosion hazard

The process probably takes place in the following stages:

1. loose deposits accumulating on the tubes slightly increase the bank flow resistance;
2. the flue gas stream starts to bypass the bank from the bottom – the flue gas flow rate drops;
3. at a smaller velocity of flue gases, the degree of fouling in the RH II reheater rises, which further reduces the flue gas flow rate between tubes;

4. a rapid accumulation of deposits occurs and flue gases flow below the bank mainly, which causes erosion of the hanging tubes and the horizontal tubes of the upper bank in duct II – Fig. 4.

Deposition probe results

Reference measurements indicate that the initial (coal and biomass co-firing, 33wt.% content, no additives) efficiency of deposition is at the level of 5.22% – Table 2. When additive was fed into the boiler, the deposition efficiency was at the level of 3.70% and 3.64%, respectively. These results point to a reduction in the rise of deposits by approximately 29%.

Table 2. Comparison of results of deposit formation on the deposition probe for the reference state and when the additive was used (t_{DP} and t_{FG} represent temperatures of the probe and flue gas)

Measurement	Sample	t_{DP}	t_{FG}	\dot{m}_{DP}	η_D
-	-	°C	°C	g/m ² h	%
33%B+67%W no additive	P32P	342	404	0.2232	5.22
33%B1+67%W1 with additive	P35P	528	585	1.4045	3.70
33%B2+67%W1 with additive	P35P	530	568	1.3841	3.64

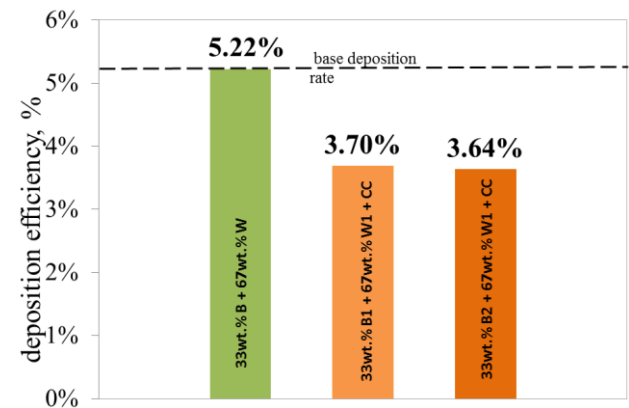


Fig. 5 Change in deposition efficiency if additive is used

DISCUSSION

In order to assess the impact of co-firing the fuels listed in Table 1 with additive on the degree of fouling of heating surfaces, calculations of the B/A factor were performed using oxide analyses of ashes (Tables 3 to 5) arising from the combustion of the investigated biomass and coal samples. The results in the form of obtained values of the B/A factor are presented in Table 6.

It can be seen in the list presented in Table 1 that biomass features a much lower content of inorganic matter compared to coal (only the B2 biomass sample – sunflower husk pellets – featured a content of ash similar to ash content in coal W1). It is also visible that the biomass ash chemical composition is different from the chemical

composition of the coal ash – Table 3. On the one hand, co-combustion of biomass with a smaller content of ash causes a decrease in the mass flow of the agent fouling heating surfaces. On the other hand, the chemical composition of the biological inorganic matter determines its strong slagging properties.

Table 3. Comparison of chemical composition of ashes from the fuels used to test additive effectiveness; SST–shrinkage, DT-deformation, HT-hemisphere, FT-flow temperatures

	Unit	no additive		with additive		
		ash	ash	ash	ash	ash
		W	B	W1	B1	B2
SiO ₂	%	46.2	18.4	37.2	10.7	38.4
Fe ₂ O ₃	%	10.2	1.25	10.6	0.72	1.87
Al ₂ O ₃	%	20.7	1.55	19	1.09	1.8
Mn ₃ O ₄	%	0.18	1.4	0.17	0.17	0.37
TiO ₂	%	0.92	0.07	0.85	0.06	0.14
CaO	%	5.4	23.1	10.7	14.2	12.9
MgO	%	3.99	6.44	5.75	8.21	5.12
SO ₃	%	5.61	3.52	9.79	5.29	4.34
P ₂ O ₅	%	0.24	10.1	0.38	4.61	5.64
Na ₂ O	%	1.24	0.78	2.06	0.19	1.3
K ₂ O	%	3.47	16.6	2.76	34.1	19.6
BaO	%	0.15	0.1	0.22	0.02	0.05
SrO	%	0.05	0.05	0.07	0.05	0.04
Cl	%	0.12	0.32	0.15	0.58	1.56
CO ₂	%	0.65	15.4	0.02	19.2	5.97
reducing atmosphere						
SST	°C	1120	700	1110	660	750
DT	°C	1140	1390	1130	1320	890
HT	°C	1160	1400	1140	1360	970
FT	°C	1210	1430	1170	1370	1040
oxidizing atmosphere						
SST	°C	1200	1000	-	-	-
DT	°C	1210	1400	-	-	-
HT	°C	1240	1450	-	-	-
FT	°C	1290	1460	-	-	-

A different chemical composition occurs also for different kinds of biomass. Energy crops and agro biomass (e.g. straw) feature higher contents of compounds of potassium, phosphorus and chlorine, which results from fertilizers used in agricultural soil cultivation. The type of soil used for energy crops is also important. Clay soils create favourable conditions for an increase in the content of Si in the plant mineral fraction compared to plants cultivated on sandy soils [10]. Another significant factor is the harvest

time and the applied harvest technology. The ash content in the analyzed fuels was included in the range of 0.7 wt.% to 5.8 wt.%. These results confirm the higher content of ash in agro biomass compared to forest biomass.

Table 4. Comparison of chemical composition of deposits arising in the area of the inter-stage reheater (deposits from the deposition probe)

	Unit	no additive	with additive	
		deposit	deposit	deposit
		P32P (B+W)	P35P (B1+W1+CC)	P35P (B2+W1+CC)
SiO ₂	%	34.4	40.2	42.7
Fe ₂ O ₃	%	19.4	10.9	8.66
Al ₂ O ₃	%	16.3	19.6	20.6
Mn ₃ O ₄	%	0.59	0.18	0.15
TiO ₂	%	0.84	0.84	0.86
CaO	%	8.59	9.26	8.77
MgO	%	4.84	4.9	4.96
SO ₃	%	1.45	4.02	3.47
P ₂ O ₅	%	0.78	0.49	0.61
Na ₂ O	%	1.7	0.86	0.79
K ₂ O	%	4.01	6.53	6.82
BaO	%	0.21	0.15	0.14
SrO	%	0.06	0.05	0.05
Cl	%	-	0.03	0.047
CO ₂	%	-	<0.01	<0.01
reducing atmosphere				
SST	°C	-	950	930
DT	°C	-	1180	1210
HT	°C	-	1230	1240
FT	°C	-	1240	1250
oxidizing atmosphere				
SST	°C	1160	-	-
DT	°C	1210	-	-
HT	°C	1250	-	-
FT	°C	1350	-	-

The factor which is of great importance in the process of deposit formation (especially in terms of the process initiation) is the content of chlorine in the fuel fed into the boiler. During the combustion process, the chlorine contained in fuel is partially released in the gaseous state as volatile compounds KCl and HCl [11]; another part of it creates salts in fly ash reducing its sintering temperature, which results in intensified deposit formation on the boiler heating surfaces.

Table 5. Comparison of chemical composition of fly ashes and deposits collected from the boiler heating surfaces

		no additive			with additive	
		deposit	deposit	deposit	ash	ash
		SH III	RH III	RH II	POP1	POP2
SiO ₂	%	24.4	27.4	44.4	43.3	42
Fe ₂ O ₃	%	9.61	6.23	7.76	7.65	8.49
Al ₂ O ₃	%	13.6	14.8	19.4	17.1	18.2
Mn ₃ O ₄	%	0.11	0.1	0.15	0.15	0.17
TiO ₂	%	0.95	1.02	0.98	0.73	0.8
CaO	%	5.99	5.24	6.66	7.94	9.53
MgO	%	3.76	3.39	4.71	4.26	5.12
SO ₃	%	19.6	20.2	6.09	0.88	0.77
P ₂ O ₅	%	2.36	1.27	0.78	0.39	0.33
Na ₂ O	%	1.73	2.13	1.31	0.6	0.8
K ₂ O	%	16.9	17.2	7.14	4.2	3.31
BaO	%	0.2	0.18	0.13	0.11	0.11
SrO	%	0.08	0.07	0.05	0.04	0.04
Cl	%	0.06	0.06	0.11	0.023	0.042
CO ₂	%	0.14	0.57	0.17	0.17	0.67
reducing atmosphere						
SST	°C	1150	1070	1140	910	960
DT	°C	1320	1310	1180	1140	1140
HT	°C	1330	1340	1190	1180	1170
FT	°C	1360	1370	1210	1200	1190
oxidizing atmosphere						
SST	°C	1150	1150	1140	-	-
DT	°C	1300	1290	1180	-	-
HT	°C	1310	1300	1200	-	-
FT	°C	1330	1310	1250	-	-

One of the methods of slagging limitation is adding sorbents to fuel or to the boiler furnace chamber directly. The sorbents combine selectively with alkaline compounds to form eutectics with a higher sintering (fusion) temperature. Table 4 presents a comparison of the chemical composition of the deposit collected during reference measurements (deposit P32P(W+B)) to the chemical composition of the deposit collected when sorbent was added to the boiler (deposits P35P(W1+B1+CC) and P35P(W1+B2+CC)). It can be seen that deposits formed when the sorbent is added feature a higher content of aluminosilicates and a substantially lower content of iron compounds. It is impossible to compare the changes in the temperature of fusion precisely because the reference sample of the P32P(W+B) deposit was tested in the laboratory in an oxidizing atmosphere whereas the samples of deposits formed when sorbent was added

(P35P(W1+B1+CC) and P35P(W1+B2+CC)) were tested in a reducing atmosphere. It can also be noticed that the content of iron compounds in the deposits formed when the sorbent is added for combustion is reduced while the content of sulphur compounds becomes higher. This chemical composition of ash results in its more glasslike nature – SiO₂ content > 50%, Fe₂O₃ <10% and CaO <7% [12, 13]. The high content of silica and the small content of iron in ash deposits result in increased viscosity and – consequently – in a weaker tendency to form deposits [14-16]. Based on the presented data – Table 4 – it may be stated that the deposits formed when the sorbent is added display a weaker tendency towards deposition.

Another important parameter that determines the ash capacity to cause slagging is the content of iron oxides. A high content of iron usually reduces ash viscosity [12], which results in a stronger tendency of the ash to form deposits. Ashes with a content of Fe₂O₃ <6% are considered, according to [17], as low-slagging. Based on the content of iron oxides in deposits, it can be seen that the deposits formed when sorbent is added feature a lower content of Fe₂O₃; therefore, their capacity to cause slagging is reduced compared to deposits formed when biomass is co-fired with no additives.

The impact of additive on fouling indices

In order to assess the impact of additive on the degree of fouling of heating surfaces, calculations of the *B/A* factor were performed as the main fouling index. The obtained values are listed in Table 6 for comparison with other indices.

The list presented in Table 6 indicates that, irrespective of the kind of co-fired biomass, this fuel has an adverse effect on the fouling degree. In practice it always intensifies the process of deposition on the boiler surfaces. Generally, at reasonable contents of co-fired biomass, it is not the amount of biomass that has a significant impact on the increase in fouling of power boilers but rather – its kind. The type of fired coal is also important – the same kind of biomass behaves differently if co-fired with low-sulphur coals, which are favoured in heat and power plants as they do not require sulphur removal systems, and if co-fired with low-calorie coals with a high ash content. There are also kinds of biomass, mainly in the form of wood pellets, which raise the *B/A* factor only slightly and at the same time – due to their low moisture content and advantageous properties of pellets in terms of milling – reduce the fouling hazard compared to the fouling caused by coal firing only.

The first column of Table 6 presents values of the ash dynamic viscosity which has to be referred to the critical viscosity value described in [18], where it is concluded that intense deposition of ash particles occurs for the value of $\mu_p < 6.7 \cdot 10^9$ Pa·s. In the case of the ashes and deposits under analysis, the value of μ_p is found to be higher than the critical value only for the P35P(W1+B1+CC) and P35P(W1+B2+CC) deposits, and it is similar to the critical value of the ashes produced when additive was used (POP1, POP2), which confirms the sorbent slagging mitigation properties.

Table 6. List of ash deposition indices

Sample	fouling indices			
	μ_p , Pa·s	S_R	$\frac{\Psi_{z\ sample}}{\Psi_{z\ ref}}$	B/A
W ash (for W+B)	$5.18 \cdot 10^4$	70.2	1.02	0.362
B ash (for W+B)	$2.02 \cdot 10^{-2}$	37.4	0.49	2.911
W+B (ref.ash)	-	69.4	1.00	0.387
W1 ash (for W1+B1+CC)	$1.19 \cdot 10^3$	57.8	1.11	0.565
B1 ash (for W1+B1+CC)	$6.07 \cdot 10^{-7}$	31.6	0.51	5.235
W1+B1 (ref.ash)	-	55.2	1.00	0.766
B2 ash (for W1+B2+CC)	$5.58 \cdot 10^6$	65.8	0.84	1.151
W1+B2 (ref.ash)	-	60.2	1.00	0.706
P32P deposit (for W+B)	$2.94 \cdot 10^2$	51.1	0.77	0.808
P35P deposit (for W1+B1+CC)	$7.22 \cdot 10^{15}$	61.6	1.13	0.543
P35P deposit (for W1+B2+CC)	$7.67 \cdot 10^{18}$	65.6	1.15	0.477
SH III deposit (for W+B)	$3.03 \cdot 10^0$	55.7	0.71	1.036
RH III deposit (for W+B)	$3.21 \cdot 10^1$	64.8	0.77	0.820
RH II deposit (for W+B)	$1.16 \cdot 10^4$	69.8	0.96	0.438
POP1 ash (for W1+B1+CC)	$1.11 \cdot 10^9$	68.5	1.25	0.410
POP2 ash (for W1+B2)	$1.45 \cdot 10^7$	64.4	1.17	0.452

The first column of Table 6 presents values of the ash dynamic viscosity which has to be referred to the critical viscosity value described in [18], where it is concluded that intense deposition of ash particles occurs for the value of $\mu_p < 6.7 \cdot 10^9$ Pa·s. In the case of the ashes and deposits under analysis, the value of μ_p is found to be higher than the critical value only for the P35P(W1+B1+CC) and P35P(W1+B2+CC) deposits, and it is similar to the critical value of the ashes produced when additive was used (POP1, POP2), which confirms the sorbent slagging mitigation properties.

Another index determining the ash tendency to cause slagging is the S_R ratio, for which the chemical composition of the fuel mineral fraction corresponding to values < 65 is considered to display a strong tendency to do so.

The S_R ratio informs of the slag viscosity:

$$S_R = \frac{SiO_2}{SiO_2 + Fe_2O_3 + CaO + MgO} \cdot 100 \quad (4)$$

A high value of S_R denotes high viscosity of slag and consequently – a low tendency to cause slagging.

The S_R values for deposits collected in the area of the inter-stage reheater are smaller than 65 ($S_R = 65.6$ only for P35P(B2)), but in the case of deposits formed when the CC sorbent was added these values are higher than values

obtained from reference measurements, which confirms the capacity of the applied sorbent to modify the ash composition so that slagging may be reduced.

A comparison of the B/A values indicates unequivocally that this parameter is decreased in the case of deposits formed when sorbent is added, confirming a weaker tendency of the sorbent to cause slagging.

CONCLUSIONS

The following conclusions may be drawn from the testing of the effectiveness of additive application to reduce slagging while co-firing biomass with coal:

- 1) The use of the sorbent involves a change in the properties of the ash produced during the combustion process.
- 2) The values obtained using all fouling indices and slagging factors prove that ash displays a weaker tendency to cause slagging if the sorbent is fed into the boiler.
- 3) The extremely strong fouling of the RH II surface probably results from its geometrical arrangement in this particular boiler area. At the designing stage, the chance that flue gases might bypass the bank taking the shortest route through the gap in the fire bridge should be avoided.

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NOMENCLATURE

A^r	ash content, wt. %
B/A	base-to-acid ratio, dimensionless
Q_i^f	lower heating value, kJ/kg
S_R	slagging factor, dimensionless
V^{daf}	volatile content, wt. %
W_t^r	moisture content, wt. %
Ψ_z	thermal efficiency, dimensionless
μ_p	dynamic viscosity of ash, Pas
τ	exposition time, h

Subscript

D	deposition
DP	deposition probe
F	duct cross-section
FG	flue gas
ref	reference

Superscript

daf	dry ash free
r	as received

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