The impact of ash content on slagging properties of coals and slagging of pulverized coal-fired boilers

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Abstract

Increasing of coal ash content leads to decrease in the efficiency of pulverized coal-fired thermal power plant, deterioration of environmental performance and increase of equipment wear rate. However, the operating personnel of the power plant as well as researchers know that increasing ash content of the coals often leads to decrease of slagging of pulverized coal-fired boilers.

Reduction of slagging with increase of coal ash content is associated with a decrease of flame temperature and reduction of coal slagging properties. However, some influencing characteristics of ash content effect on slag-forming properties of coals and slagging of boilers are less obvious, at least non-linear and even not unique.

Slagging of boilers due to ash content, among other things, depends on the maximal and local temperatures of the flame. With the increase of ash content, the adiabatic temperature of combustion reduces as well as average temperature of the flame in the cross-section of the combustion zone. The change in gas temperature at the outlet of the furnace, even without considering changes in slagging of waterwalls, is ambiguous and depends on the size of the furnace and the ash content variation range.

Slag-forming properties of high-ash coals (A^d>20%) depends weakly on ash content. For coals with low to moderate ash content, the effect can be significant, though with the opposite sign for different coals and indicators. The increase in the ash content of the oxidized coals is associated ultimately with the enrichment in calcium. It is natural that the increase in ash content due to this factor has the opposite effect on the slag-forming properties as compared to the growth of ballast owing to the rock.

Increasing of coal ash content leads to decrease in the efficiency of pulverized coal-fired thermal power plant, deterioration of environmental performance and increase of equipment wear rate. However, the operating personnel of the power plant as well as the researchers know that increasing ash content of the coals often leads to decrease of the slagging of pulverized coal-fired boilers. There are examples where the recommendations to switch over the combustion of coal with higher ash content were sufficient for a significant improvement of the slagging conditions or its complete elimination. It is clear that when exceeding Initial Slagging Temperature ϑ_{sl} with the increase of ash content (normalized ash content A^d/Q_i^r for boilers), intensity of the slag deposits increases. However, the intensity of the slag deposits formation is not one of the main characteristics of the slagging process, determines just the mode of operation of the cleaning, and slag removal devices.

Some characteristics of ash content influencing the slag-forming properties of coals and slagging of boilers are less obvious, at least non-linear and even not unique.

The dependence of pulverized coal-fired boilers slagging on ash content, as well as on operation conditions is associated with changes in maximum and local temperatures of the flame and possible changing of slagging properties of the deposited ashes. At that, the influence of these factors can both coincide and have the opposite effect.

1. Change of the slagging *properties*

The increase in ash content of most coals results in reduction of the coal propensity to slag furnace. Thus, Berezovsky coal, which is characterized by highest slagging capacity among all coals burned at Russian heat power plants has an ash content equal to or below A^d=8%, while that of the least slagging Ekibastuz coal accounts for A^d=39-48 %.

The Ural Laboratory ranked the propensity of various coals to slag furnace based on the expert evaluation (according to responses to the questionnaire of specialists of boiler industry companies, institutes and engineering firms) [1]. It was confirmed that the index P_S, reflecting coal propensity to slag furnace, can't be reliably characterized by just one particular indicator, for example, by ash fusibility, or a tendency to form strong primary deposits. Thus, it is necessary to use a set of indicators or their combinations defining different aspects of the process. The expert assessment of P_S^{ex} index, shown in Fig. 1, confirms the thesis about the specificity of the reduction of slag-forming properties with increasing ash content of the coals.

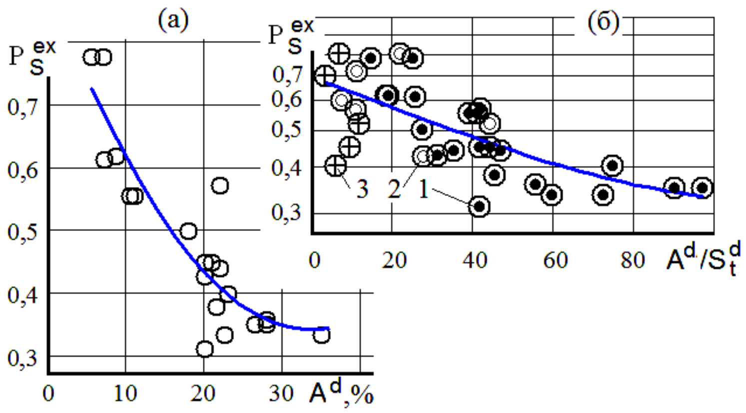

Fig. 1. Expert assessment of coal slag-forming properties, P_S^{ex}.
(a) for coals with sulfur content S_t^d<0.65% and different ash content A^d;
(b) depending on the ash to sulphur ratio (A^d/S_t^d),
1 - S_t^d<0.65%, 2 - S_t^d=1-2%, 3 - S_t^d>2%.

For non-oxidized coals with acid ash composition, including the majority of Russian and Kazakh coals, reduction of slagging properties is associated with an increase in Initial Slagging Temperature (the temperature of the start of slagging) t_{sl} (Fig. 2) and a decrease in strength of formed deposits (or in other terms, with increase in the temperature at which the fixed strength is reached). Moreover, the difference between the combustion temperature ϑ_f and the Initial Slagging Temperature t_{sl} ($\Delta t=\vartheta_f- t_{sl}$) decreases. According to the theory and laboratory research findings, the increase in ash content slows the transformation of pyrite into solid refractory oxides, thereby creating conditions for the formation of strong ferrous primary deposits. However, a decisive role is obviously plaid by large formations pyrite content, which depends on the coal formation prehistory and is irregular with regard to ash content (Fig. 2b).

In contrast, the propensity to form solid sulphate-calcium deposits is reduced with increasing ash content of the concrete coals and the aggregate of domestic coals, or even the complete absence of such deposits when combusting high-ash coals (Fig. 2c). The foregoing does not exclude the existence of fuels with a high tendency to form sulphate–calcium deposits characterizing at the same time by high ash content, such as, for example, Balkan lignites. The propensity (potential) to slag the furnace and form strong selective deposits is shown in dimensionless normalized indicators in Figs. 1 and 2. At that, when P=0.2, the deposits are not observed or the potential is low, while at P>0.6 the potential is high.

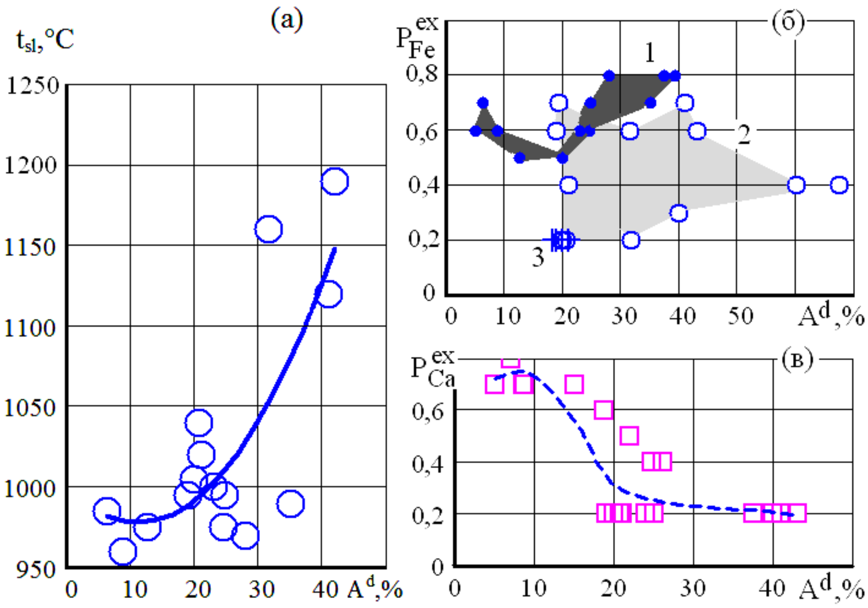

Fig. 2. The experimental values of Initial Slagging Temperature (a), the propensity to form solid ferrous (b) and sulphate-calcium (c) deposits based on the research results of Ural Heat Engineering Institute when combusting coals with different ash content in power boilers.

1 - brown coals of a low rank, 2 - brown coals of a high rank and hard coals of low rank (3B, D, G – according to the Russian classification, subbituminous coals - according to the American classification), 3 – hard coals of high rank.

The presentation of research data in Figs. 1 and 2 depending on the ash content is not optimal, and is used just to illustrate the availability or lack of the impact of the analyzed factor. To predict the performance of the slagging properties one uses the combination of traditional data and specific laboratory tests. In assessment methods provided by UralVTI and Ural Laboratory, in addition to the information on the bulk chemical composition of ash and technical characteristics, data on the content of pyrite sulphur, active alkalis and calcium, as well as ash sintering data are used; see, for example [2, 3].

Noted effect of ash content on slagging properties of coal aggregate is primarily due to the change in the ash composition. For coals with different types of ash, the effect of changes in the composition is manifests itself not equally in terms of magnitude and sign. Consider two types of ash: with the acidic composition and with high content of alkaline earth components, mainly, calcium. The coals with high content of alkaline elements in the form of ion-exchange elements and those contained in the ordinary salts, such as the American lignites of the Northern Great Plains or brown German (Rhine) coals, are not used in the Russian energy sector and thus not considered in the present paper. Moreover, divide the coals on oxidized and non-oxidized ones, for which a change in the ash composition depending on ash content occurs according to the opposite laws.

Inherent ash, especially of the coals with low degree of coalification, is enriched by alkaline and alkaline-earth components, whereas the composition of the excluded ash is usually mainly represented by silicate and aluminosilicate minerals of acid composition. With increasing ash content due to the increase in the amount of the excluded ash at its constant composition and the composition of the inherent ash, the bulk chemical composition is strictly determined by the mixing equations (1):

$$(R_nO_m)_j=b_j+a_j\cdot Pa = b_j+a_j\cdot(100/A^d),\ \% \qquad (1)$$

where $(R_nO_m)_j$ – is one of the ash forming elements in the form of oxides (SiO_2, Al_2O_3, TiO_2, Fe_2O_3, CaO, MgO, K_2O, Na_2O); $Pa=100/A^d$ – is the linearizing indicator of ash content; a_j, b_j – are the empirical coefficients of the linear equation for each of elements, different for various coals.

For example, Fig. 3 shows the change in the content of the main elements of the ash depending on ash content of 2B brown coal of the largest Russian strip mine Borodinsky based on the studies of commercial samples and data processing in the form of equation (1).

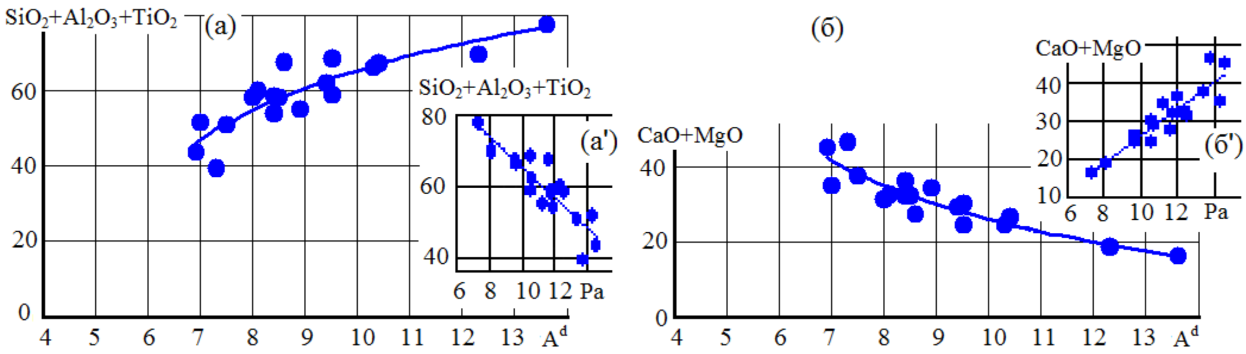

Fig. 3. Change in content of acid (a) and alkaline-earth elements (b) in Borodinsky coal depending on the ash content; (a′), (b′) –the same, depending on $Pa=100/A^d$ index. Dots – are the experimental values, lines correspond to calculations by the equations of type (1).

For hard coals with high degree of coalification, where the distinction between inherent and excluded ash is less pronounced, as well as for coals with a variable composition of enclosing rocks, noted dependencies are poorly expressed or absent at all. Also, it is obvious that for coal aggregate composed on the principle of selecting coals with different type of ash and formation prehistory, chemical composition of fly ash may change erratically depending on ash content. Nevertheless, the broad aggregate of Russian and Kazakhstan coals with different metamorphic rank, geology and formation prehistory, have the trends specific to individual coals.

Ash content also increases at coals oxidation. Solvent power of edge waters in the oxidized coal increases due to dissolved carbon-acid and humic acids. In contrast to the growth of the ash content due to rock ballasting, the increase of coal oxidation leads to an increase in the content of the alkaline-earth metals (calcium and magnesium) even for the coals with a quite high content of these elements in unoxidized coals like Berezovsky coal [4]. Since during the coal oxidation, the amount and composition of inherent ash do not remain constant, for aggregate of coal samples with different degree of oxidation, the analysis based on use of mixing equations of type (1) and the ratio $100/A^d$ as linearizing indicator, is inapplicable. Therefore, it is advisable to handle information on the mineral matter of oxidized coals in the form of two-factor analysis, at least in a linear form (Fig. 4a).

Temperature characteristics of ash (initial slagging temperature t_{sl} and temperature of fixed strength of deposits $t_{\sigma=idem}$) have extreme points depending on the composition, as is shown for example in Fig. 4b. Here the ash composition is expressed by the ratio $ko=(SiO_2+Al_2O_3+TiO_2)/(CaO+MgO+K_2O+Na_2O)$, adopted based on the development of UralVTI, which better characterizes the initial slagging temperature and temperature of fixed strength of deposits.

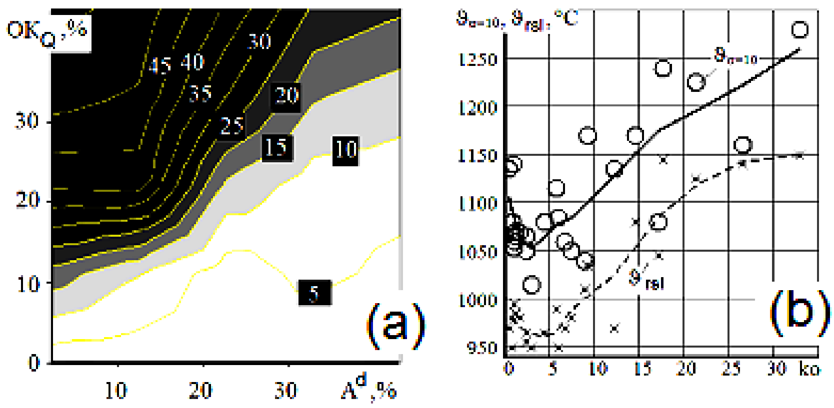

Fig. 4. Statistically average contour lines of the CaO content (a) in the mineral matter of Kuznetsk coals depending on the ash content and degree of oxidation (OK_Q – degree of oxidation with regard to reduction of combustion heat) and change in the initial temperature of actual slagging ϑ_{rsl}, as well as temperature $\vartheta_{\sigma=10}$ corresponding to the breaking strength of formed in situ deposits at σ=10 kPa, obtained on coal fired test facility of UralVTI depending on the composition of fly ash (b).

It is obvious that for coals with acid ash composition, with increasing ash content (the ko ratio, respectively) the Na_2O), adopted based on the development of UralVTI, which better characterizes the initial slagging temperature and temperature characterizing the strength of deposits, increase that along with a reduction in combustion temperature (Fig. 5) provides a reduction of slagging potential.

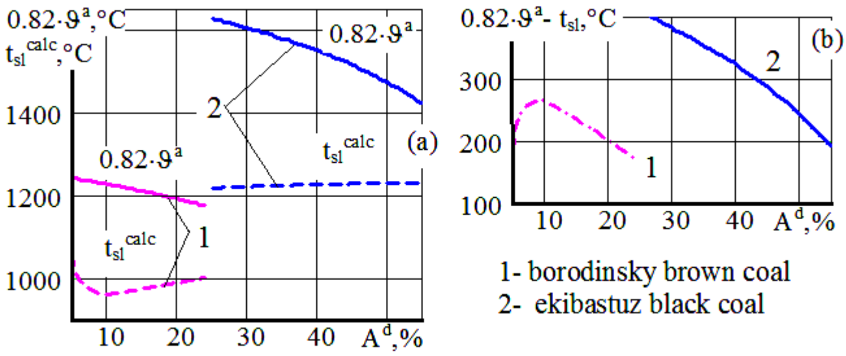

Fig. 5. A change in the calculated temperature values $0.82 \cdot \vartheta^a$ and the initial slagging temperature t_{sl}^{calc} (a), and their difference (b) depending on the ash content evidence from Borodinsky brown coal with a high content of alkaline-earth elements, and Ekibastuz high-ash coal with a high content of acidic components; ϑ^a – is adiabatic combustion temperature.

For low-ash coals with high content of alkaline-earth elements, the initial slagging temperature is reduced with the increase of ash content while the strength of the ash deposits increases. However, the gained experience shows that the low-ash coals do not belong to low-slagging coals. This is likely due to the increased combustion temperature, noticeable amplification of the formation of strong primary sulphate-calcium deposits with significant change in the ash composition, even at a small change in ash content, as well as factors of such coals combustion conditions.

Effect of the ash content growth during the coals oxidation with regard to the properties of slag (secondary) deposits and slagging of boilers is ambiguous and, above all, depends on the ash-forming mineral composition of the original (non-oxidized) coal, the degree of oxidation and the property of slag deposit, which is crucial from the standpoint of slagging of particular boiler. The initial slagging temperature t_{sl} for coals with acid ash composition decreases, while for those with the basic composition of fly ash – remains approximately constant or increases [4]. The tendency to form strong sulphate-calcium deposits increases with increasing ash content in the course of oxidation, while potential and rate of formation of the strong ferrous primary deposits decreases. The sign and the degree of the change in iron content at oxidation and the associated increase in the ash content varies for different coal fields, however, principle is the fact that the iron content in the pyrite composition (FeS_2) at the oxidation is reduced. Thus, in the studied sample of Berezovsky oxidized coal (A^d=14.5%) the content of iron was Fe_2O_3=16.2% versus 9.8% in the sample of non-oxidized coal (A^d=6.0%), though the iron content in the inherent ash increased from Fe_2O_3=4,5% to 15.2%, while decreased in the excluded ash.

The excluded mineral matter of oxidized coal contains not only less amount of pyrite than that in non-oxidized coal, but furthermore, it exists in more dispersed form. In excluded ash of non-oxidized coal, from one-half to one-third of iron is presented in the form of pyrite in the shape of separate grains, whereas in the oxidized coal, less than one-fourth is presented in the form of a gel-like structureless mass [5].

2. Influence on the temperature of the flame and gases

It is obvious and also is confirmed by the practice that at the same composition and amount of the mineral matter of coal, the danger of slagging of furnace waterwalls increases when combusting fuels, providing higher temperature in the flame. Thus, when predicting the slagging, we should take into account the factors influencing the temperature level.

The adiabatic combustion temperature decreases with the increase in ash content. The average flame temperature in the combustion zone decreases with increasing the ratio of the maximum temperature in the central zone to the average temperature. Note that the decrease in adiabatic temperature of combustion and the flame temperature with increasing ash content (Fig. 5) is caused to a significant extent by the increase of hydrate moisture in coal. The hydrate moisture content depends on the mineral composition, mainly on the type of clay minerals.

The decrease of combustion temperature with increasing ash content, when burning hard coals, has basically an impact on slagging of furnace waterwalls, including the local ones. With regard to brown coals, the noticeable factor may be the increased tendency to form strong ferrous primary deposits as well as the change of the degree of ash melting in case of its high content.

Slagging of the heating surfaces at the furnace outlet depends on the ratio of furnace exit gas temperature ϑ_T'' (FEGT) and gas temperature $(\vartheta_T'')^{per}$, permissible for slagging. For different boilers and coals, these indicators change variously depending on the ash content, even qualitatively. As discussed above, the dependence of the temperature indicators and strength of the slag deposits, which determine gas temperature permissible for slagging $(\vartheta_T'')^{per}$, has points of extremum dependant on ash content. Besides, temperature FEGT is ambiguous with regard to the ash content. It depends, in particular, on the degree of flame emissivity as well as the dispersion of the radiant flux and thermal efficiency of furnace waterwalls.

Increase of ash content leads to increase of flame emissivity, though the dispersion of the radiant flux also increases. Cumulatively, without taking into account changes in the thermal efficiency coefficient, increase of ash content leads to a decrease of temperature ϑ_T'' (FEGT) for low-ash coals and non-large boilers, and conversely, to an increase of temperature ϑ_T'' for ash coals and powerful boilers (Fig. 6). Accordingly, the temperature difference $\Delta\vartheta=\vartheta_T''- (\vartheta_T'')^{per}$ for various fuels and boilers can have a different sign depending on ash content.

Change with the same sign of furnace exit gas temperature and gas temperature permissible for slagging depending on ash content somewhat eliminates strengthening of slag-forming properties of coals with lower ash content, such as is the case for 500 MW unit boiler when replacing the Ekibastuz coal by Kuznetsk coal [6]. The transition from low ash coals to high-ash coals improves the slagging conditions. Note that in this paper the permissible temperatures ϑ_T'' (Fig. 6) are given as comparative figures. Actual permissible values $(\vartheta_T'')^{per}$ should be assigned taken into account the variability of coal characteristics. For example, for

Kansk-Achinsk coal-fired boilers (including, Borodinsky coal) it is proposed that $\vartheta_T'' \leq 1130°C$ [7].

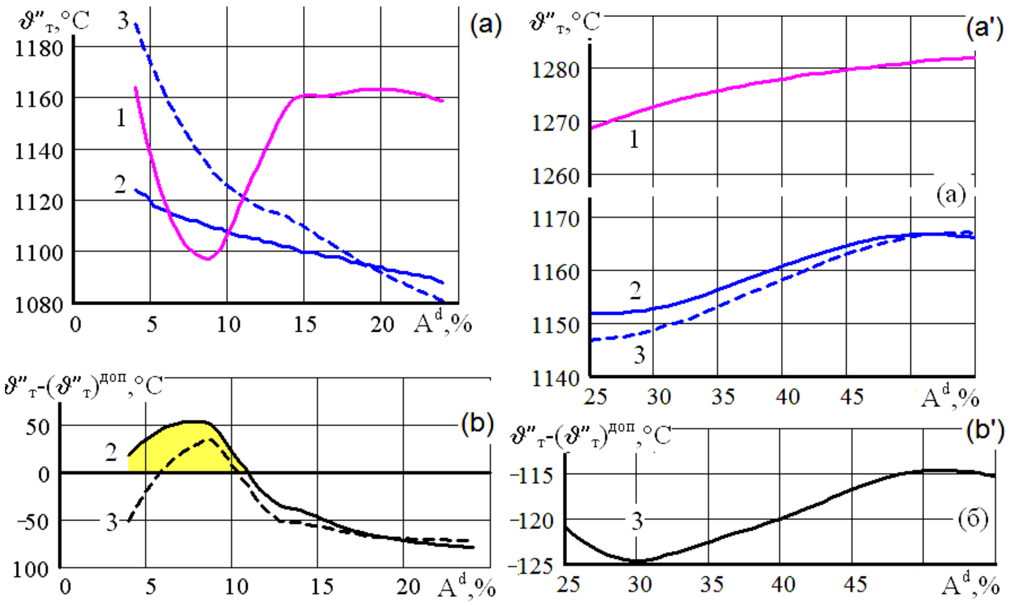

Fig. 6. Furnace exit gas temperature (FEGT) (a,a') and the difference between the actual gas temperature and the gas temperature at the outlet of the furnace permissible for slagging (b,b').

1 – temperature of gases at the outlet of the furnace permissible for slagging ($\vartheta t''$)^{per}; 2 – temperature calculated according to a standard method ϑ_t'' at a constant thermal efficiency of waterwalls [8]; 3 – the same temperature for projected thermal efficiency, dependant on ash content;

shown as an example [9]; 4 – calculation according to zonal model [10] for equally contaminated waterwalls; a,b – Boiler E-500, Borodinsky coal; a',b' – Boiler PK-39, Ekibastuz coal.

Conclusions

1. The increase in ash content of the coal typically reduces boiler slagging problem, though has negative impact on the environment and lowers the efficiency of the boilers.

2. When using off-design coals and coals with variable ash content, it is necessary to analyze the changes in slagging properties in conjunction with changes in gases temperature in the furnace, including also consideration of the influence of ash content on the thermal efficiency of furnace waterwalls.

3. For hard coals with acid ash composition, increase in ash content increases the initial slagging temperature and reduces the strength of deposits that is complemented also by the reduction of the combustion temperature. For high-ash coals, temperature rise at the outlet of the furnace can contribute to slagging of the superheater, though this change is quite small and is partly compensated by growth of gas temperature permissible for slagging.

3. For low-ash brown coals, growth of ash content within a certain range reduces initial slagging temperature as well as temperature permissible for slag formation at the furnace outlet that can cause problems of slagging at specific conditions, though this factor is often smoothed over by the decrease in gas temperature in the furnace and reduction of propensity to form strong sulfate – calcium deposits.

4. Continuation of the research will be appropriate in terms of studying the influence of ash content on the formation of strong ferruginous deposits and prediction of the thermal efficiency of the waterwalls.

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