The influence of intense preliminary mechanical processing on the slag formation in coal-fired utility boilers

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Abstract. Burdukov et al. [1] showed experimentally that enhancement of coal reactivity when micronized in a high-impact disintegrator mill makes it possible to attain self-igniting and self-sustaining (autothermal) compact-flame combustion in a cold environment. But with intensive grinding of coal, the mineral part of the fuel is also being converted, which can lead to both a decrease and an increase in the intensity of the formation of deposits. The effect of grinding on the mineral matter of coal and the formation of deposits in a 5 MW pilot-scale combustor are presented. The experiments showed a decrease in the intensity of formation of deposits after grinding of coal by disintegrating mill as compared to grinding in the ball–tube mill.

1. Introduction
The intense preliminary mechanical processing of fuel is a promising technology in heat-power engineering, which makes it possible to increase considerably the reactivity of fuel [2]. Studies on the production of mechanically activated coal ground in a mill of the disintegrator type and its combustion on fire test benches have been carried out at the Kutateladze Institute of Thermophysics, Siberian Branch, Russian Academy of Sciences [1]. The technology proposed for the combustion of coals ensures the ignition and flame stabilization of a coal-dust torch without the use of highly reactive gas and black-oil fuel. It is believed that this processing can substantially affect the processes of both mineral matter conversion and ash deposition.

Only studies on the structural changes and reaction properties of coal after intense mechanical processing were reported in the currently available literature [3, 4]. However, there are no publications related to studying the influence of mechanoactivation on the intensity of the formation of deposits. The aim of this work was to study the influence of intense preliminary mechanical processing on the slag formation in coal-fired utility boilers. Coals of different degrees of metamorphism were considered: Kuznetsk black coal and brown coal of Kansk-Achinsk basin. These coals were ground by means of the disintegrating mill and the ball–tube mill.

2. Problem statement and research methods
Coal (Table 1 summarizes its proximate analysis) was crushed in a ball–tube mill and a disintegrator-type mill. The distinctive feature of crushing in a ball–tube mill and a disintegrator is the mode of action on the coal matter: this is abrasion and squeezed impact in the ball–tube mill or free impact in the disintegrator.

The X-ray spectral fluorescence analysis was used for determining the composition of the products of the thermal conversion of mineral substances and their amounts in particles with different sizes [5].
The method includes the drying of an analyzed test sample at 105°C for 1.5 h with the subsequent heat treatment at 960°C (for 2.5 h) and mixing with a flux (66.7% lithium tetraborate, 32.8% lithium metaborate, and 0.5% lithium bromide) in a ratio of 1 : 9 (the total weight of the mixture was 5 g). The mixture was melted in platinum crucibles in a Lifumat-2.0-Ox induction furnace (Germany).

### Table 1. Technical characteristics of the initial coals.

| Coal          | W<sub>daf</sub> | A<sub>daf</sub> | V<sub>daf</sub> | C<sub>daf</sub> | H<sub>daf</sub> | S<sub>daf</sub> | O<sub>daf</sub> | Q<sub>s</sub>   |
|---------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|---------------|
| Kuznetsk coal | 5.4            | 22.3           | 34.7           | 75.57          | 5.66           | 0.55           | 16.44          | 29.7          |
| Brown coal    | 30             | 12             | 46             | 71.4           | 4.0            | 0.3            | 13.7           | 26.1          |

The study of the influence of the method of grinding coal on the formation of deposits was carried out using experimental and computational modelling. The object of the study was an uncooled probe that was placed in the chamber of the combustor (figure 1). The combustor considered here simulates the 5 MW pilot-scale experimental rig (figure 1) [6, 7]. It consists of two stages: the first stage (denoted in the schematic, figure 1 as burner) is a cylindrical swirl chamber with a diameter of 315 mm and length of 1525 mm. The micronized coal premixed with the primary air by an ejector was fed tangentially to the burner through a vaneless spiral. The second stage (denoted in figure 1 as after burner chamber or combustor) is a coaxial cylindrical duct with an inner diameter of 1000 mm and length of 2820 mm, also equipped with a tangential entry for secondary air (which reinforces the swirling motion). The burner spiral has an aperture for a gas torch used to ignite the coal–air mixture.

![Figure 1. A sketch of the 5 MW experimental rig.](image)

To determine the rate of primary and secondary air and coal consumption, computational studies were carried out. The study of the formation of deposits on the probe requires the necessary temperature conditions. The temperature when placing the probe should be higher than the initial slagging temperature at 100 - 200 °C. The results of numerical simulations showed that the rate of primary and secondary air should be 500 and 400 m³/h respectively, the consumption of coal should be 90 kg/h.

The complete combustion model considers the process as a flow of incompressible non-isothermal multicomponent reacting gas-particle mixture, using Euler-Lagrangean frames for the gas-phase and particles, respectively. The field variables are described by Reynolds averaged equations for the conservation of mass, momentum, enthalpy and mixture fraction of species concentration. The gaseous phase is treated as a single-phase fluid in which the effects of the dispersed reacting coal particles on the gaseous phase were accounted for by the PSI-Cell method. The RANS equations are closed with the standard high-Re-number k-ε turbulence model. More details about the comprehensive model can be found in Chernetskiy et al. [7]. Coal particle devolatilization as well as char combustion are approximated by one-component schemes using the kinetic-diffusion model. More details about
this model can be found in Chernetskiy and Dekterev [8]. In the model, formation of slag deposits is estimated based on the initial slagging temperature. By initial slagging temperature it is meant the gas temperature at which the formation (sticking) of slag deposits begins at the noted difference between the gas temperature $\vartheta$ and the temperature of the surface $t_s$. The initial slagging temperature can be determined sufficiently precisely from empirical expressions depending on the chemical composition of ash [9].

3. Results and discussion

Upon crushing in different mills, different redistributions of the mineral matter occurred. The same trends are observed for the types of coal. Figures 2–6 illustrate the results of X-ray fluorescence analysis for two types of grinding. The separation of coal dust into fractions according to particle sizes and the X-ray spectral fluorescence analysis of the fractions obtained showed that coal ground in the ball–tube mill was characterized by an increased concentration of mineral components in the small fraction of standard grinding (figure 2). This was caused by the predominance of easy to grind minerals containing silicon (figure 3). Crushing in the disintegrator led to the more uniform distribution of the inorganic components of coal over fractions. This was primarily due to the fact that the disintegrator exerts a more intense effect on coal matter and more effectively decomposes organomineral aggregates. Because of this, the small fraction is enriched in elemental calcium (figure 4), iron-containing minerals (figure 5), and clay minerals.

Figure 2. Distribution of the ash component in the coal dust fractions of coal after crushing in (blue line) the disintegrator and (black line) the ball–tube mill. (1) – Kuznetsk black coal and (2) – brown coal.

Figure 3. Distribution of the SiO$_2$ component in the coal dust fractions of coal after crushing in (blue line) the disintegrator and (black line) the ball–tube mill. (1) – Kuznetsk black coal and (2) – brown coal.

Figure 4. Distribution of the CaO component in the coal dust fractions of coal after crushing in (blue line) the disintegrator and (black line) the ball–tube mill. (1) – Kuznetsk black coal and (2) – brown coal.

Figure 5. Distribution of the Fe$_2$O$_3$ component in the coal dust fractions of coal after crushing in (blue line) the disintegrator and (black line) the ball–tube mill. (1) – Kuznetsk black coal and (2) – brown coal.
The results of the experiments on the formation of deposits in the combustor during the combustion of Kuznetsk black coal are presented in figures 6 and 7. Analysis of the amount of deposits showed that after grinding in a disintegrator, their weight is 20% less than when grinding in a ball–tube mill.

Figure 6. The formation of deposits on the probe after the combustion of Kuznetsk coal was crushed in a ball–tube mill.

Figure 7. The formation of deposits on the probe after the combustion of Kuznetsk coal was crushed in a disintegrating mill.

Figures 8, 9 shows the results of numerical simulations. The colors correspond to the intensity of the formation of deposits (figure 10). Coal dust is supplied with primary air through the burner. The main part of the coal dust moves in the centre of the combustion chamber, forming ash particles. Ash particles collide with the probe. Depending on the composition of ash and temperature conditions, the particles either remain in the form of deposits or fly further. Some particles move tangentially along the chamber walls due to the swirling flow. As a result of this, part of particles form deposits at the edges of the probe. Despite the same temperature conditions in the combustion chamber, the amount of ash deposited after burning coal, which was crushed in the disintegrating mill, is less.

Figure 8. Numerical simulations of the slag formation after the combustion of Kuznetsk coal crushed in a ball–tube mill.

Figure 9. Numerical simulations of the slag formation after the combustion of Kuznetsk coal crushed in a disintegrating mill.

Figure 10. The intensity of the formation of deposits, kg/m²s.
This is primarily due to the size of the particles. Particles of a small size interact less with the probe surface. The proportion of small particles after grinding in the disintegrator is smaller. It is necessary to note the qualitative coincidence of the results of numerical simulations and experiment.

4. Conclusions.
The separation of coal dust into fractions according to particle sizes and the X-ray spectral fluorescence analysis of the fractions obtained showed that coal ground in the disintegrator led to more uniform distribution of the inorganic components of coal over fractions. This was primarily due to the fact that the disintegrator exerts a more intense effect on coal matter and more effectively decomposes organomineral aggregates. The saturation of small fractions with iron compounds can lead to a decrease in the primary strong ferrous deposits due to more rapid burning of pyrite and conversion of iron-containing compounds. A large proportion of fine particles after grinding with a disintegrator as compared with grinding in a ball–tube mill reduces intensity of slagging.

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