Improving the energy efficiency of flaring in pulverized coal-fired boilers at TPPs of the Siberian Federal District by mechanochemical activation of coal

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Abstract. The heat power system of the Siberian Federal District is almost coal-based: energy generation at coal-fired TPPs makes up 87.2%. But due to low reactivity of coals fed to the pulverized coal boilers, expensive high-reactive fuel oil is used to ignite and light the pulverized coal flame, which is a technological and economic problem. To increase the energy efficiency of flame burning of coal, an increase in their reactivity due to mechanochemical activation is considered using the technology developed at IT SB RAS. For several different coals, experimental studies on burning were carried out at a 5 MW pilot setup using mechanochemical activation of coal. These studies showed reliable ignition and stable access to the autothermal coal combustion, which indicates an increase in coal reactivity and the ability to replace fuel oil with coal.

1. Introduction
The Siberian Federal District (SFD) plays a key role in the energy supply of Russia. Significant hydrocarbon reserves are concentrated in its territory, including more than 80% of Russian coal. Energy generation at thermal power plants (TPPs) in the SFD is about 51% of the total generation (thermal, hydropower, solar) and it is almost coal-based [1]. Coal TPPs in the SFD make up 87.2%; coal generation is envisaged by the Program of Coal Industry Development in Russia and the Energy Strategy of Russia for the period until 2035.

The TPPs operate mainly on coal and lignite of Siberian deposits. The main coals are presented by the coal of the Kuznetsk deposit, and the main lignites are supplied from the Kansk-Achinsk fuel and energy complex. High-calorie coals have unstable characteristics in terms of volatile composition and ash content. Low-calorie lignites with high volatility come with fluctuating calorific value and high humidity, and significant variation in ash content per working fuel. However, their proportion is increasing in the fuel and energy balances of regional TPPs. The TPPs use hundreds of steam boilers of the BKZ, PK, and TP types with pulverized coal flaring, produced by the Barnaul, Podolsk and Taganrog boiler plants. Due to the low reactivity of coals, the energy efficiency of coal flame burning is low; problems mainly concern lighting and flame stabilization in boilers, especially when using lignite. Therefore, to light the flame, highly reactive fuel oil is used in the amount of 0.1% - 3.5% of the total fuel. The total annual consumption of fuel oil in these boilers is about 200 thousand TOE (about 1% of the total fuel consumption) [2]. Consumption of fuel oil is problematic in terms of its supply, storage in the cold season, heating, explosion safety, deterioration of environmental and economic indicators of burning, deficit, and, most importantly, high cost, which leads to increased energy tariffs. The cost of fuel oil can exceed the cost of coal by up to 5 - 7 times (for natural fuel) and up to 3 - 4 times (for...
equivalent fuel). The replacement of highly reactive fuel oil during ignition and lighting of pulverized coal boilers is an urgent task.

Four available boilers with a flame burning of various coals at four TPPs with problems of ignition and lighting are presented in the Table below with the characteristics of coals and existing combustion problems. Therefore, fuel oil is used for ignition and lighting [3,4]; the used volume of fuel oil $V_{\text{fuel oil}}$ is given in the Table. For these coals, the improvement of energy efficiency of coal flaring is considered for fuel oil replacement, while for boilers, the investment attractiveness of projects for replacing fuel oil ignition and lighting with mechanically activated coal.

2. Improvement of energy efficiency of flame burning of coal by mechanical activation

In the IT SB RAS, along with consideration of the well-known traditional characteristics, such as caloric value, volatility, ash content, and humidity, which determine the energy efficiency of coal combustion, an increase in the chemical activity of coal due to mechanochemical activation is considered. The Institute has achieved a technology advance in this field [5 - 7].

Mechanochemical activation is achieved by mechanochemical micro-grinding of coal to the particles with the sizes of up to 15 - 40 μm using special energy-intensive mills, MD disintegrators - dispersers of finely chopped disk grinding with dust collection (by a cyclone or bag filter). The MDs are produced at the Novosibirsk enterprise Prodselmash LLC in the range of capacities from 50 (MD-50) to 3000 kg/h (MD-3000). The energy consumption for coal micro-grinding is about 30 - 50 kWh/TOE.

Fine and ultrafine grinding of coals up to 15-40 μm results in a change of their physicochemical characteristics. When coal is finely dispersed, it is crushed with an increase in the specific surface $S$, and aggregation of fine particles at sufficient grinding duration leads to a decrease in this surface. Under mechanical influences in special mills, local concentrations of mechanical and thermal energy lead to the breaking of chemical bonds and formation of free radicals, including macroradicals; the chemical activity of coals increases, which leads to accelerated oxidation and ignition. This leads to a sharp increase in the reactivity of coal in various processes and chemical reactions.

3. Experimental studies of mechanically activated fuel burning

The experiments were carried out employing a pilot setup with a thermal capacity of 5 MW (Figure 1). During the experiment, temperatures along the entire length of the experimental setup were measured, and the gas analysis at the combustion chamber outlet was performed.

![Figure 1. Experimental setup of up to 5 MW.](image)
highly reactive combustible mixture, after partial gasification, enters the afterburner, where it mixes with the secondary air fed tangentially.

The experiments were carried out using Kuznetsk coal of G and TR grades (Table 1). In the experiments, the coal consumption was 150 kg/h, the excess air coefficient was $\alpha = 0.5; 0.7$. The results of autothermal combustion and gasification are shown in Figure 2.

![Graphs showing gas concentration vs. temperature for gasification of mechanically activated coal of various grades: 1 – G, 2 – TR; a – $\alpha = 0.5$; b – $\alpha = 0.7$.](image-url)

**Figure 2.** Dependence of gas concentration on the temperature at gasification of mechanically activated coal of various grades: 1 – G, 2 – TR; a – $\alpha = 0.5$; b – $\alpha = 0.7$.

A decrease in air leads to an increase in the maximum concentration of H$_2$ and CO. Stable autothermal combustion of dust suspension of Kuznetsk coals of G and TR grades was obtained due to their mechanically activated grinding. The data on ignition and combustion of mechanically activated coals of G and TR grades make it possible to recommend the micro-grinding technology for these coals in oil-free ignition systems of boiler plants.
Table 1. Projects to substitute fuel oil ignition and lighting with mechanically activated coals at TPPs of the Siberian Federal District.

| TPP boilers | Used coals | Problems of ignition and lighting | \( V_{\text{fuel oil}} \) (caloric value) | \( V_{\text{coal}} \) (caloric value) | TOE | TOE | Installed mills | Economic performances | \( T_{\text{av}} \) |
|-------------|------------|----------------------------------|---------------------------------------------|---------------------------------------|-----|-----|----------------|------------------------|--------|
| Boiler PK-40-1 of Belovo SDPP, 320 tons of steam/h, “Siberian Generating Company”, Kemerovo Region | Kuznetsk coals of grade D and G \( Q_r = 5500 \text{kcal/kg} \) \( V_{\text{daf}} = 37 - 42.5\% \) \( W_r = 8 - 12\% \), \( A_d = 8 - 13\% \) | Variable quality composition | 152.0 \((Q_r = 9800 \text{kcal/kg})\) | 270.8 | MD-3000 (2 main, 1 reserve) | 1.7 | 11.9 | 2.8 | 4.3 |
| Boiler PK-10P of South–Kuzbass SDPP, 210 tons of steam/h, PJSC “South-Kuzbass SDPP”, Kemerovo Region | Kuznetsk coals of grade TR, TROK \( Q_r = 5600 \text{kcal/kg} \) \( V_{\text{daf}} = 17\% \) \( A_d = 16.8\% \) | Low volatility, High ash content | 299.7 \((Q_r = 9800 \text{kcal/kg})\) | 524.5 | MD-1100 (4 main, 1 reserve) | 1.2 | 15.6 | 5.6 | 2.8 |
| Boiler BKZ - 420 - 140 PT of Krasnoyarsk SDPP-2, 420 tons of steam/h, PJSC “OGK-2” | Kansk-Achinsk lignite \( Q_r = 3561 \text{kcal/kg} \) \( V_{\text{daf}} = 49\% \) \( W_r = 30.8\% \) | Low calorie value, high humidity | 256.6 \((Q_r = 10000 \text{kcal/kg})\) | 720.6 | MD-3000 (4 main, 1 reserve) | 1.7 | 22.1 | 4.8 | 4.6 |
| Boiler PK-24 of Irkutsk Heat Plant-10, 270 tons of steam/h, PJSC “Irkutskenergo” | Mugunsk and Azeisk lignite \( Q_r = 4000 \text{kcal/kg} \) \( V_{\text{daf}} = 40\% \) | Low calorie value, high humidity | 109.7 \((Q_r = 9800 \text{kcal/kg})\) | 268.7 | MD-2500 (2 main, 1 reserve) | 1.6 | 11.2 | 2.1 | 5.3 |
4. Experimental studies of mechanically activated fuel combustion

The positive experimental results on the combustion of mechanically activated coals, which showed an increase in reactivity, allow considering the projects for replacing fuel oil ignition and lighting in boilers.

For annual replacement of fuel oil $V_{\text{fuel oil}}$, shown in the Table 1, annual consumption of coal $V_{\text{coal}}$ is calculated from the equality of heat energies of annual consumptions of fuel oil and coal:

$$V_{\text{fuel oil}} \cdot Q'_i \text{fuel oil} = V_{\text{coal}} \cdot Q'_i \text{coal}$$

$$V_{\text{yc}} = \frac{V_{\text{fuel oil}} \cdot Q'_i \text{fuel oil}}{Q'_i}$$

where $Q'_i \text{fuel oil}$ is calorie value of fuel oil, $Q'_i \text{coal}$ is calorie value of coal.

The project for the organization of oil-free ignition and lighting with the replacement for coal involves new costs for the purchase of mills and manufacture of non-standard equipment for coal dust and air supply to the burner, and it should be attractive for investment. The investment attractiveness of the projects is estimated by the payback period. A project is considered attractive and is subject to review if the payback period $T_{av}$ is at the level of 5-7 years for effective investment projects of existing enterprises [8].

The payback period of the project is determined based on economic costs incurred by the enterprise:

$$T_{av} = K_{add} / E_{current}$$

where $K_{add}$ represents one-time additional capital costs for implementation of the project, $E_{current}$ is saving annual operating cost during the project implementation.

For the considered projects, $K_{add}$ is presented in Table 1, and it is determined as:

$$K_{add} = K_{\text{main mill}} + K_{\text{reserve mill}} + K_{\text{ns equip}} + K_{\text{prep}}$$

where $K_{\text{main mill}}$ and $K_{\text{reserve mill}}$ are acquisition costs for the main and reserve mills, depending on their productivity, $K_{\text{ns equip}}$ is the cost of manufacturing the non-standard equipment for coal dust and air supply, $K_{\text{prep}}$ is the cost of preparatory work for oil-free ignition (design, construction, and installation works).

To select the mills for each boiler (capacity, number), recommendations for its ignition, the grade of coal, ignition hours are taken into account. The installed mills with the designation of productivity (kg of o.e./h) and acquisition cost for one mill $K_{\text{mill}}$ are shown in the Table 1. Based on expert evaluations of technology developers, the costs of manufacturing the non-standard equipment and preparatory work for modernization of ignition and lighting are taken in comparison with the costs of installed mills as:

$$K_{\text{ns equip}} = K_{\text{prep}} = K_{\text{main mill}}$$

Saving annual operating costs $E_{current}$ are achieved by replacing expensive fuel oil with cheap coal, which may also provide investment attractiveness. It is reduced by the cost of coal micro-grinding.

Saving annual operating costs $E_{current}$ presented in the Table 1 can be estimated as:

$$E_{current} = C_{\text{fuel oil}} - C_{\text{coal}} + C_{\text{elecr.}} = P_{\text{fuel oil}} \cdot V_{\text{fuel oil}} - P_{\text{coal}} \cdot V_{\text{coal}} + C_{\text{elecr.}} \cdot B_{\text{elecr.microgr.}} \cdot V_{\text{coal}}$$

where $C_{\text{fuel oil}}$ represents annual costs of fuel oil replacement, $C_{\text{coal}}$ represents annual costs of replacing coal, $C_{\text{elecr.}}$ are annual costs for electricity spent on coal micro-grinding, $P_{\text{fuel oil}} = 22154$ rub./TOE is the price of fuel oil purchasing; $V_{\text{fuel oil}}$ (TOE) is the annual volume of replaced fuel oil, $P_{\text{coal}} = 1301$
rub./TOE is the price of lignite purchasing, \( P_{\text{coal}} = 2066 \) rub./TOE is the price of coal purchasing, \( V_{\text{coal}} \) is the annual volume of replacing coal (TOE), \( B_{\text{elec.,microgr.}} = 30 – 50 \) (kWh/TOE) is specific consumption of electricity spent on micro-grinding of one ton of coal, \( P_{\text{coal}} = 2066 \) rub./TOE is the tariff for company auxiliaries.

Costs of purchasing fuel oil, coal, electricity for in-house needs are: \( P_{\text{fuel oil}} = 22154 \) rub./TOE, \( P_{\text{coal}} = 2066 \) rub./TOE, \( P_{\text{coal}} = 2066 \) rub./TOE;

**Conclusion**
The attractive investment projects for replacing fuel oil used for ignition and lighting with coal activated by mechanochemical treatment is proposed for some pulverized coal boilers at TPPs of Siberian Federal District. The estimated project payback periods are at the level accepted for cost-effective projects of existing enterprises (5 years and lower). These projects may be proposed to consider upgrading the ignition and lighting system.

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